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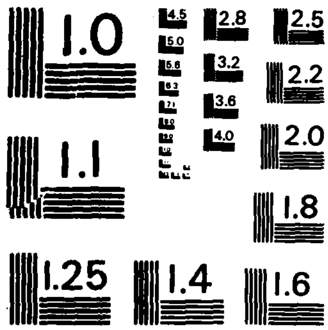
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Report No. CG-D-35-85

AD-A163 568

SUMMER 1983 LEEWAY DRIFT EXPERIMENT

L. NASH AND J. WILLCOX

U.S. Coast Guard Research and Development Center
Avery Point, Groton, Connecticut 06340

INTERIM REPORT

AUGUST 1985

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SAMUEL F. POWEL, III
Technical Director
U.S. Coast Guard Research and Development Center
Avery Point, Groton, Connecticut 06340

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This report is the second on leeway and the seventeenth in a series which documents the Improved Probability of Detection in Search and Rescue (POD/SAR) Project at the U.S. Coast Guard Research and Development Center.

16. Abstract

A new method of determining leeway was tested using three life rafts. The method differed from previous methods in that (1) the current was estimated from an array of Lagrangian drifters instead of a single drifter, (2) a land-based microwave tracking system was used to determine positions, (3) two of the life rafts were instrumented to monitor the relative wind at the rafts, and (4) all analysis used the apparent wind relative to the current at the raft.

All three life rafts were undrogued, canopied, circular with diameters of 6 to 7.5 feet, empty except for 80 to 100 pounds of equipment, and ballasted. The three ballasting systems were (1) two half-cylinder ballast bags with a 6-inch draft, (2) a toroid ballast system with a 14-inch draft, and (3) a hemispheric ballast system with a 28-inch draft.

The method was successful in differentiating the leeway of the lightly ballasted raft from the more heavily ballasted rafts. The leeway speed of the lightly ballasted raft was comparable to results in previous studies. The leeway speeds for the more heavily ballasted rafts were substantially less than those in a previous study. The leeway direction of the lightly ballasted raft was dependent on the raft's orientation to the wind with the two ballast bags acting as a keel. The more heavily ballasted rafts drifted directly downwind.

Wind speeds ranged from 2 to 11 knots with waves of 0 to 2 feet and swells up to 4 feet.

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METRIC CONVERSION FACTORS

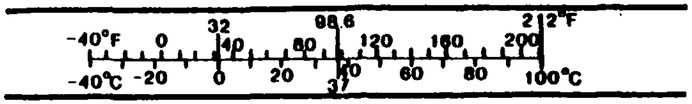
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (WEIGHT)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (EXACT)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures. Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (WEIGHT)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	0.125	cups	c
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (EXACT)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

INTRODUCTION

This report presents the results of the Summer 1983 Leeway Drift Experiment conducted by the U.S. Coast Guard Research and Development Center. Leeway is defined as that movement of a craft through the water caused by the wind acting on the exposed surface of the craft. Leeway of life rafts and small craft is of interest in predicting the locations of survivors at sea.

The purpose of this experiment was to test a new method of determining leeway. The method differed from previous methods in that:

1. The current was estimated from an array of drifters instead of a single drifter.

2. A land-based microwave tracking system was used to track the rafts and drifters. This provided very accurate positions every two minutes on each object.

3. Two of the rafts were partially instrumented for wind measurements.

4. All analysis was done using the apparent wind relative to the current at the raft. This is important in low winds and strong currents.

The three life rafts used in this experiment were an RFD 6-man MK3A, a Switlik 4-man, and a Givens 6-man life raft. All three life rafts were (1) undrogued, (2) canopied, (3) circular with diameters of 6 to 7.5 feet, (4) unloaded except for approximately 80 to 100 pounds of equipment, and (5) ballasted. The RFD had two half-cylinder ballast bags. The Switlik and Givens had a deep-draft ballast system [as defined in National Search and Rescue Manual (SAR Manual)]. The Switlik had a toroid ballast system with a 14-inch draft. The Givens had a hemispheric ballast system with a 28-inch draft. The RFD was tested with the door closed and open. The Switlik and Givens were tested only with the door closed.

RESULTS

The results of the experiment are limited by two factors. The first is the mild environmental conditions during data collection. Wind speeds ranged from 2 to 11 knots with waves of 0 to 2 feet and swells up to 4 feet. The second factor is that the wind at low speeds varied considerably in direction and magnitude over short distances. Therefore, the wind measured at an anchored platform may have been different from the wind at the test raft.

The method was successful in detecting the differences in the leeway speed of the lightly ballasted raft (RFD) from the more heavily ballasted rafts (Switlik and Givens). The leeway speeds for the RFD 6-man life raft with door closed were similar to the SAR Manual's recommendation for a canopied life raft with ballast buckets. The leeway speeds for the Switlik 4-man and the Givens 6-man life rafts were much slower than the SAR Manual's recommendation for canopied rafts with deep-draft ballast systems. This may be due to the fact that this study used the average current of the upper three feet of the water instead of the much thicker layer that was used as the basis for the SAR Manual's recommendation (Scobie and Thompson, 1979).

The RFD raft was deflected to the right or left of the wind depending on which sector of the canopy was to windward. The leeway angle was correlated with the orientation of the raft to the wind and the wind speed.

For the Switlik raft, the leeway angle could not be correlated with either the orientation of the raft to the wind or the wind speed. This suggests that the measured leeway angles are due to the variability of the wind field and are not true leeway angles.

The RFD and Switlik rafts always assumed an orientation so the force of the wind was acting on the material between the tubes of the canopy. The individual canopy support tubes were never directly to windward. The orientation of the Givens raft was not monitored.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future research should include some estimate of the vertical profiles of wind and current used in drift predictions. This will ensure that the leeway data collected using different methods are compatible with the Computer Assisted Search Planning system (CASP) and are comparable with each other. The difference between this report and previous research on deep-draft, ballasted life rafts might be resolved in this manner.

To correctly model a search object's long-term drift, the tendency of a craft to change its leeway angle from one side of the wind to the other must be addressed. This can be accomplished by: (1) studying a craft's response to different frequencies of wind shifts and the variability of the wind fields, and (2) conducting long-term drift studies. A long-term drift study should have drift periods exceeding 36 hours and containing at least one wind shift.

Leeway data on deep-draft, ballasted life rafts with drogues need to be collected as there is no information available at this time.

RECOMMENDATIONS FOR OPERATIONAL LEEWAY GUIDANCE

A significant difference exists between the leeway information for canopied deep-draft, ballasted life rafts in the SAR Manual and in this report. The difference cannot be adequately resolved at present. The authors recommend that this uncertainty be considered when making drift predictions. The present SAR Manual recommendation should be used as the upper limit. The lower limit could be either zero leeway similar to a person-in-the-water or a speed of 0.1 knot for winds of 5 knots and greater.

Circular life rafts with the underwater portion symmetric about a vertical axis through the raft's center have small, if any, true leeway angles. The present guidance is to use a leeway angle of ±35 degrees. A value of ±10 degrees is adequate if the apparent wind relative to the current is considered. Otherwise, a higher value should be used depending on the current and wind. The variability or uncertainty of the wind and current is assumed to be addressed elsewhere in the prediction.

CHAPTER 1
INTRODUCTION

1.1 THE EXPERIMENT

This report presents the results of the Summer 1983 Leeway Drift Experiment. The U.S. Coast Guard Research and Development Center (R&DC) conducted the experiment in Block Island Sound off Fishers Island, New York, during the period 6 July through 3 August 1983. The test used three undrogued canopied life rafts, each with a different ballasting system.

The purpose of the experiment was to test a new method of determining leeway. Leeway is defined as that movement of a craft through the water caused by the wind acting on the exposed surface of the craft. This report does not address survivability or merits of the life rafts used. This experiment is part of a continuing effort to improve drift predictions for search and rescue (SAR).

This work is being conducted at the R&DC, Avery Point, Groton, Connecticut, under the project "Increased Probability of Detection in Search and Rescue."

1.2 BACKGROUND

1.2.1 Leeway in Search and Rescue

A key element of a successful search is the correct prediction of the location of the search target. For a search object located on the surface of the water, the search planner must consider some of the following sources of drift:

1. Sea currents,
2. Wind-driven currents,

3. Tidal currents,
4. Miscellaneous currents from river runoff, longshore currents, etc.
5. Wave- and swell-induced drift, and
6. Leeway.

For the search planner, the components of leeway are leeway speed and angle. Leeway speed is the speed at which the wind will push an object through the water. Leeway angle is the angle off downwind to which the object will sail.

The current leeway information available in the National Search and Rescue Manual (SAR Manual) is presented in Table 1. The listed references are believed to be the original studies on which the equations are based, since the SAR Manual does not list references. Separate equations for winds above and below 5 knots (2.6 m/s) are used. For winds above 5 knots (2.6 m/s), the equations are an empirical fit of data. For winds below 5 knots (2.6 m/s), the data was insufficient. However, since there can be no leeway without wind, a straight line was drawn from the origin to the leeway for 5 knots (2.6 m/s) of wind.

The SAR Manual advises that the leeway speed for rafts in Table 1 should be increased by 20 percent for the addition of a canopy and decreased by 20 percent for the addition of ballast buckets.

1.2.2 Previous Leeway Investigations

The Woods Hole Oceanographic Institution conducted a series of leeway drift studies from November 1943 through April 1944 using the Navy Mark I, II, IV, VII and the Army A-3 and E-1 rafts (Pingree, 1944). These small one- to five-man rafts were tested loaded, with and without drogues. The tests were conducted in three marine environments: Buzzards Bay, Massachusetts; off of Boca Grande Island, Florida; and in the open ocean northeast of the Bahama Islands. Pingree (1944) presented only the results of the experiment as the leeway rate relative to the upper 15 feet of the ocean (Figures 1 and 2). Note the considerable scatter at wind speeds of 4 knots and less.

TABLE 1

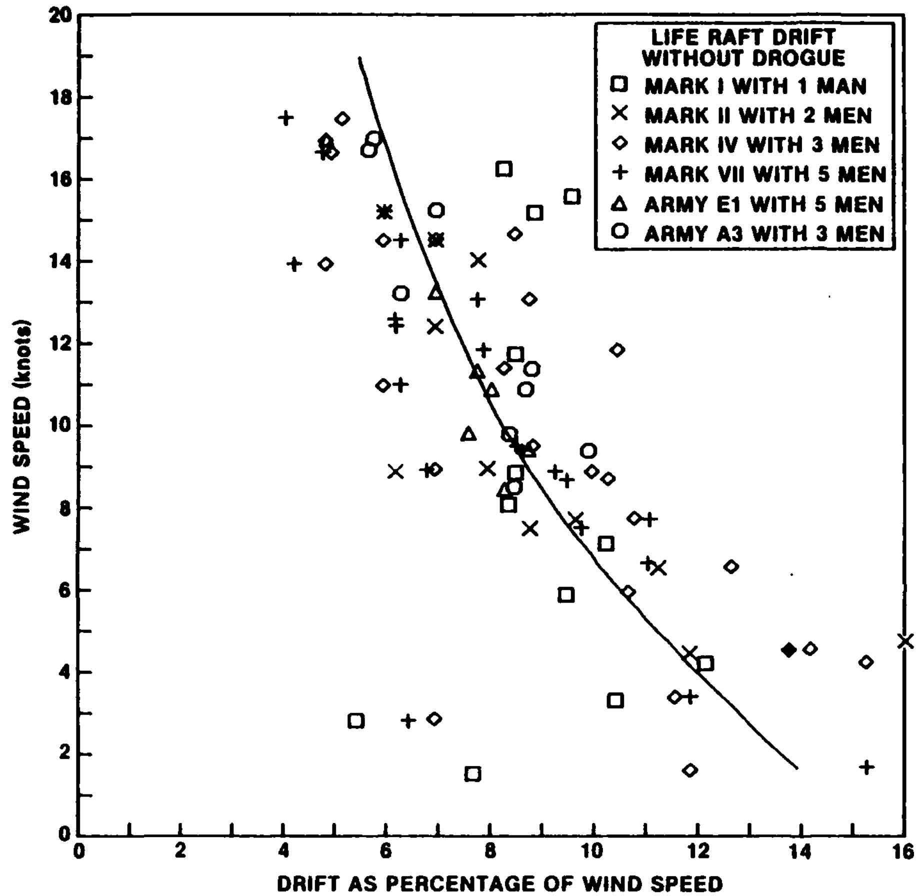
CURRENT LEEWAY INFORMATION AVAILABLE IN SAR MANUAL

TYPE OF CRAFT	WIND SPEED*	LEEWAY SPEED*,†	LEEWAY ANGLE (deg)	REFERENCE
Light-displacement cabin cruisers (no drogue) Outboards (no drogue) Rafts without canopies/ballast system (no drogue) Rafts with canopies and ballast buckets	0-5 (0-2.6) 5-40 (2.6-20.6)	0.078U 0.07U + 0.04 (0.07U + 0.02)	±35	Hufford and Broida (1974)
Light-displacement cabin cruisers (with drogue) Outboards (with drogue) Rafts without canopies or ballast system (with drogue) Canopied raft with deep-draft ballast system	0-5 (0-2.6) 5-40 (2.6-20.6)	0.026U 0.05U - 0.12 (0.05U - 0.06)	±35	Hufford and Broida (1974) Scobie and Thompson (1979)
Large cabin cruisers	0-40 (0-20.6)	0.05U	±60	Chapline (1960)
Medium-displacements sailboats Fishing boats (e.g., trawlers, trollers, tuna boats)	0-40	0.04U	±60	Chapline (1960)
Heavy-displacement, deep-draft sailing vessels	0-40	0.03U	±45	Chapline (1960)
Surfboards	0-40	0.02U	±35	Chapline (1960)

NOTE: Leeway speed and angle information available in the National Search and Rescue Manual is listed with the most likely original source of the equations.

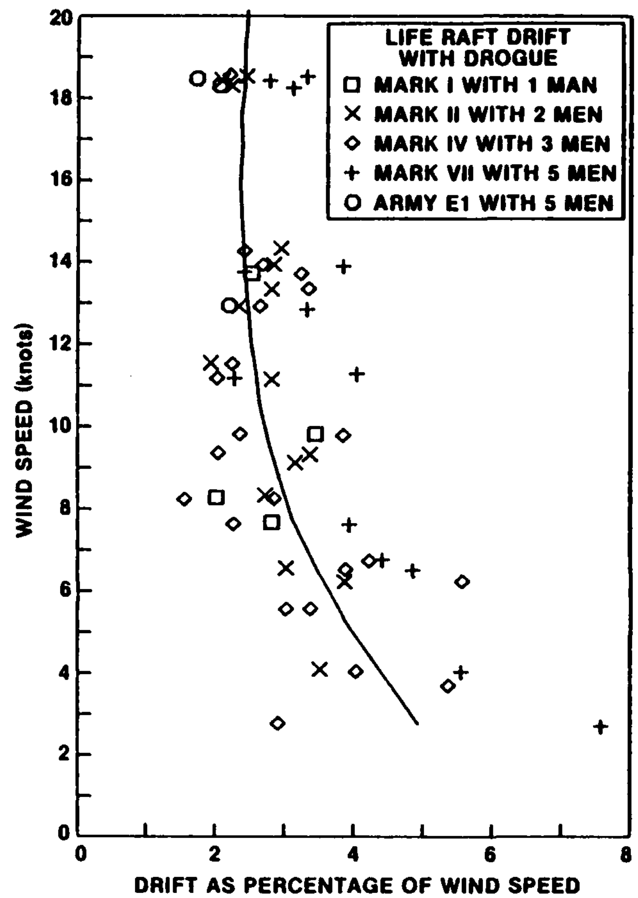
* Values and equations in parentheses are for meters/second (m/s), if different. All others are in knots.

† U is wind speed.



RESULTS BASED ON TESTS CONDUCTED BY WOODS HOLE OCEANOGRAPHIC INSTITUTION JUNE 15, 1944.

Figure 1. Life Raft Drift Without Drogue (Pingree, 1944)



RESULTS BASED ON TESTS CONDUCTED BY WOODS HOLE OCEANOGRAPHIC INSTITUTION JUNE 15, 1944.

Figure 2. Life Raft Drift With Drogue (Pingree, 1944)

In 1959, a leeway study called "Operation Spindrift" was conducted offshore of Hawaii using vessels and small craft from the Coast Guard Auxiliary, local commercial fishermen, and other willing boaters (Chapline, 1960). The drift due to currents was removed by recording all positions relative to a 300-foot (91.4 m) long by 15-foot (4.6 m) wide fine mesh drift net. The boats started their drift 2 to 3 miles (3.7 to 5.6 km) upwind of the net. Positions were taken by radar ranges and visual bearings every half hour by the observation vessel. No mention was made of the use of drogues. Chapline (1960) used a linear model passing through the origin for the analysis (Table 2). This model assumes that leeway is a constant percentage of wind speed for a particular craft.

TABLE 2

LEEWAY RATES FOR MODERATE TO FRESH WINDS (Chapline, 1960)

GROUP	CRAFT	PERCENT OF WIND SPEED
I	Surfboards	2
II	Heavy-displacement, deep-draft sailing vessels	3
III	Moderate-displacement, moderate-draft sailing vessels and fishing vessels such as trawlers, trollers, sampans, draggers, seiners, tuna boats, halibut boats, etc.	4
IV	Moderate-displacement cruisers	5
V	Light-displacement cruisers, outboards, planing hull types, skiffs, etc.	6

From November 1972 through 1974, the United States Coast Guard Research and Development Center conducted a series of leeway experiments in Fishers Island Sound and Block Island (Hufford and Broida, 1974). The experiments used drogued and undrogued small craft ranging from 9 to 24 feet (2.7 to 7.3 m) in length. The current was measured using a dye patch. All positions were recorded relative to the dye patch using aerial photography.

Results were presented for 12- to 22-foot (3.7 to 6.7 m) small craft with winds ranging from 5 to 20 knots (2.6 to 10.3 m/s). A 12-foot (3.7 m) raft without canopy or ballast system was included as one of the small craft. The leeway angle varied from 5 to 45 degrees for small craft with a greater keel plane area and 5 to 60 degrees for craft with small keel plane area. Use of a drogue reduced leeway angle by approximately one half.

Leeway speed was not significantly different for the different craft, so all were combined into drogue and undrogued categories. For undrogued craft, the leeway speed (U_L) was found to be:

$$\text{knots: } U_L = 0.04 + 0.07\, U_W$$

$$\text{m/s: } U_L = 0.02 + 0.07\, U_W$$

where U_W is the wind speed. For small craft with drogues, the relationship is:

$$\text{knots: } U_L = -0.12 + 0.05\, U_W$$

$$\text{m/s: } U_L = -0.06 + 0.05\, U_W \,.$$

Hufford and Broida (1974) reported that an increase in seas from 2 feet (0.6 m) to 4 feet (1.2 m) resulted in an approximately 15 percent increase in leeway speed.

The U.S. Coast Guard Oceanographic Unit conducted a series of leeway experiments from January 1968 through March 1971 (Morgan, et al, 1977). The test craft were the MK7 life raft without canopy, a 16-foot (4.9 m) outboard motor boat, an 18-foot (5.5 m) motor launch, and a 30-foot (9.1 m) utility boat with cabin. The MK7 life raft is a 7-man oblong raft without any ballast system and is approximately 12 feet (3.7 m) long. The current was measured by means of a buoy with a 28-foot (8.5 m) diameter parachute drogue. All positions were determined by visual bearings and radar ranges from the research vessel. Position and wind data were collected approximately every 20 minutes. The results in Figure 3 were determined by smoothing a linear regression done on 5-knot (2.6 m/s) intervals of wind speed.

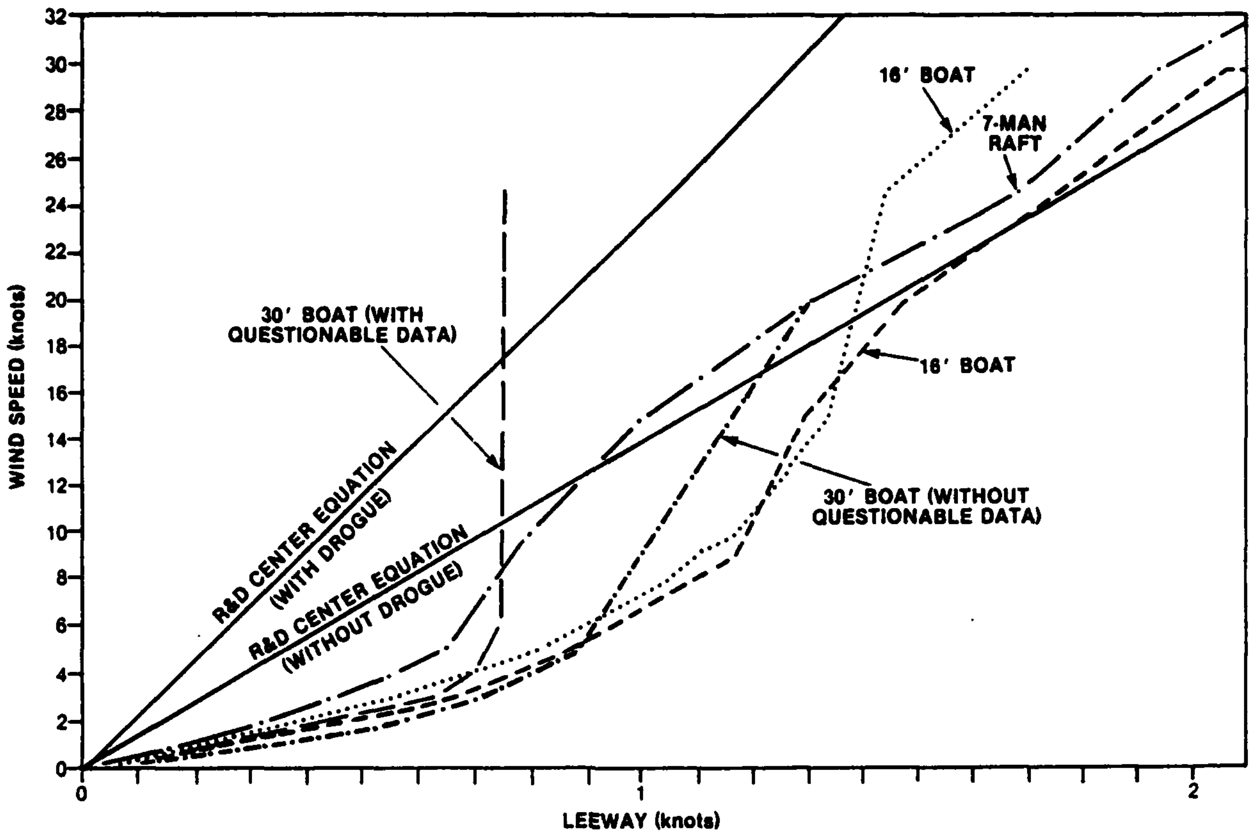


Figure 3. Leeway versus Wind Speed (Adapted from Morgan, 1977. The lines denoted as "R&D CENTER EQUATION" are from Hufford and Broida, 1974.)

Morgan (1978) presented the results for the MK7 life raft with drogue (sea anchor). The leeway factor (leeway rate) for winds above 5 knots (2.6 m/s) was found to be "essentially constant at .04." The leeway angle was found to be 35 degrees to the right for a 5-knot (2.6 m/s) wind and approximately 0 degrees for wind speeds above 10 knots.

The U.S. Coast Guard Oceanographic Unit with the USCGC EVERGREEN (WAGO-295), on a cruise from 15 February 1978 through 7 March 1978, conducted a leeway study for undrogued, canopied life rafts (Scobie and Thompson, 1979). The current was measured by a buoy equipped with a 10-foot (3 m) square window shade drogue. The rafts for whom results were calculated were: one 6-man, one 20-man, and one 25-man life raft, all of which had improved ballast systems. The rafts were

weighted with sand bags to represent the loading of passengers. For winds of 10 to 35 knots (5.1 to 18 m/s) and seas of 5 to 15 feet (1.5 to 4.6 m), the leeway speed was found to be:

$$\text{knots:}\quad U_L = 0.042\, U_W + 0.060$$

$$\text{m/s:}\quad U_L = 0.042\, U_W + 0.031$$

where U_L = leeway and U_W = wind speed. The leeway angle was less than 30 degrees for 78 percent of all drifts.

The U.S. Coast Guard Research and Development Center overlayed leeway experiments with other experiments in January 1979, February 1980 and February 1981 (Osmer, et al., 1982). The first two experiments were conducted at sea with USCGC EVERGREEN. The current was measured using a buoy drogued to 98 feet (30 m) by window-shade drogues. Positions were determined from EVERGREEN using ranges by radar and a microwave ranging system, and radar or visual bearings. The third experiment was conducted inshore using a microwave tracking system for positioning. The current was determined using expendable surface current probes. The experiments used a variety of 4- to 6-man life rafts with and without canopies and drogues. Due to the considerable scatter in the data, no conclusions were reached. Osmer, et al. (1982) recommended that the microwave tracking system be used in shore-based mode for future leeway experiments.

CHAPTER 2
THE EXPERIMENT

2.1 EXPERIMENT DESIGN

The concept of the experiment is that an array of Lagrangian current markers [i.e, Microwave Tracking System (MTS) drifters] deployed around a drifting test craft, (e.g., a life raft) can be used to determine the surface current acting on the craft. After the effect of the current is subtracted the craft's movement, the leeway relationships can be calculated. The execution of the concept requires accurate and frequent measurement of the wind, and positions of the craft and drifters.

On a typical test day, the on-scene monitor boat would anchor the wind station in the test area. Then the boat would deploy the drift array (see Figure 4) so that the test raft would drift close to the wind station around the middle of the drift. As the raft moved through the array, the monitor boat deployed additional drifters to keep the raft surrounded, and recovered the drifters no longer required for the array.

The craft's aspect to the wind was monitored to gain insight into the reasons for leeway divergence and differences in leeway speed. Any change in leeway that could not be explained by a change in either the environmental loading or the craft's aspect to the wind would have to be due to errors in measurement.

2.2 DATA COLLECTION

The two main types of data collected were position and wind. The collection of position information is discussed in Section 2.2.1. The anchored wind station is described in Section 2.2.2. The wind instrument onboard the craft is described in Section 2.2.3. The recording of environmental data onboard the monitor boat is discussed in Section 2.2.4.

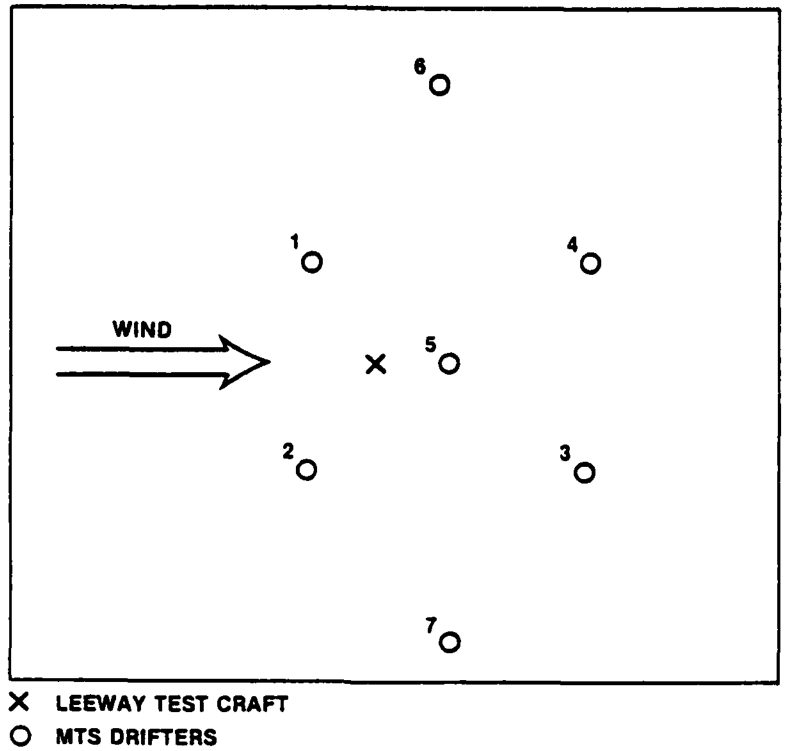


Figure 4. Typical Orientation of Array upon Deployment

2.2.1 Position

The positions of the deployed drifters, raft, wind station, and monitor boat were collected approximately every 2 minutes. The positions were determined by a microwave tracking system (MTS), which consisted of a Motorola Mini-Ranger III tracking system controlled by a microcomputer, a Hewlett Packard HP 9845B. Motorola advertises the Mini-Ranger III to be accurate up to ±3.3 yards (3 m) with ideal geometrics. The accuracy for the Block Island Sound installation should be ±10.9 yards (10 m).

The MTS configuration consisted of a master station (R&D Control) located at Mount Prospect, Fishers Island, New York, and the two reference stations located on the lighthouses at Watch Hill, Rhode Island, and at Montauk Point, Long Island, New York.

The MTS used the New York state coordinate plane in meters in lieu of latitude and longitude. The coordinate plane is a Cartesian coordinate system with the x- and y-axes

increasing to the east and true north, respectively. It is much easier to compute distance from this system since it lacks the dichotomy of distance calculation of the latitude/longitude system. The errors due to the curvature of the earth are insignificant for the small test area; therefore, the complexity of angular systems such as latitude/longitude is not necessary.

A description of the MTS operation principles can be found in Edwards, et al (1981).

2.2.2 Wind Station

The primary source for wind information was the anchored wind station which transmitted continuously via VHF-FM to R&D Conrol. R&D Control would then sample the wind information with every round of positions, i.e., approximately every 2 minutes.

The wind station consisted of a Brooks and Gatehouse Hercules System 190 interfaced with a VHF-FM data link and mounted on a 16-foot (4.9 m) Boston Whaler. The Hercules System 190 is a microprocessor-controlled instrument package designed primarily for sailing yachts and racing. The system as installed on the Boston Whaler consisted of a fluxgate compass, cup anemometer and wind vane, and a microprocessor. The wind vane and anemometer were mounted 7 feet (2.1 m) above the water. The wind speed and direction, as presented to R&D Control, were averages of 60 seconds by the microprocessor.

The accuracy and resolution of the wind sensor is presented in Table 3. The accuracy of the whole wind station under the conditions encountered (3-foot seas and 20-knot wind speeds) should be better than ± 10 degrees and $\pm$ 2 knots ($\pm$ 1.03 m/s).

TABLE 3

ACCURACY AND RESOLUTION OF BROOKS AND GATEHOUSE HERCULES SYSTEM 190 INSTALLED ON ANCHORED WIND PLATFORM

WIND INFORMATION	ACCURACY	RESOLUTION
Speed		
Less than 10 knots (5.14 m/s)	± 0.5 knots (0.26 m/s)	0.1 knot (0.05 m/s)
10 knots or greater (5.14 m/s)	± 5%	1.0 knot (0.51 m/s)
Direction	± 2°	1°
Time	-	Winds averaged over 60 seconds

2.2.3 Wind at the Raft

The raft's orientation to the wind was recorded by a Meteorological Research, Inc., Mechanical Weather Station Model 1071 (see Figure 5). It recorded wind direction, wind run, and temperature in English units on a strip chart. Wind run is a count of the distance of air that passes by and is converted to speed when divided by time. The recorder, mechanisms, and batteries were housed in a cylindrical body with the wind vane and cup anemometer mounted on top. The body was 8 inches (20 cm) in diameter and 12.5 inches (23 cm) in height. The complete instrument was 25 inches (64 cm) in height and weighed 21 pounds (9.5 kg).

The weather station was placed on the raft to measure only the relative wind direction since the station lacks a compass. The accuracy of the relative wind direction after being measured from the chart was estimated to be ±8 degrees.

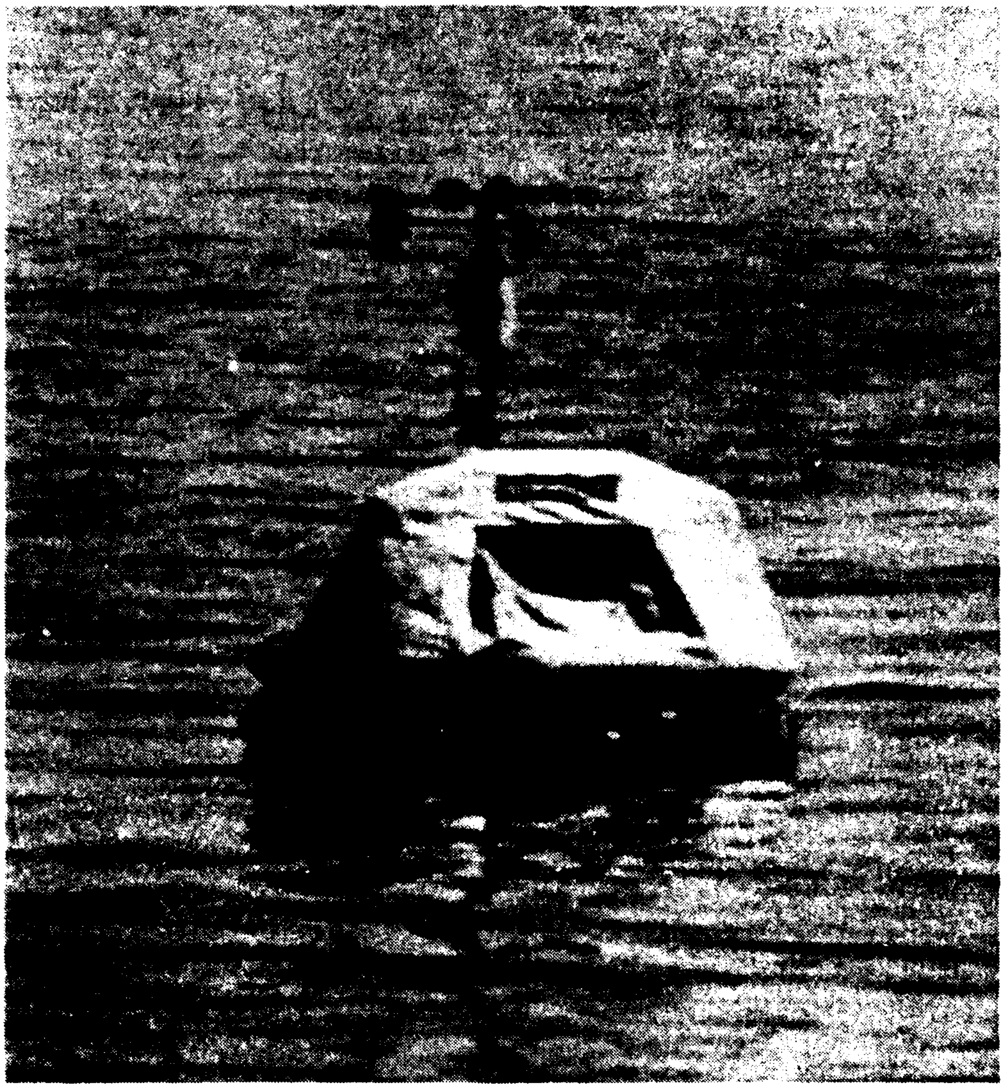


Figure 5. Meteorological Research, Inc., Mechanical Weather Station Model 1071 Mounted on Switlik 4-Man Life Raft

2.2.4 Monitor Boat

Except for sea surface temperature, the environmental parameters given in Figure 6 were recorded on the monitor vessel, operations permitting, every 20 minutes. The wind was measured with the boat dead-in-the water using a hand-held instrument. The height of the measurements was approximately 11 feet (3.4 m). Swell and wave height were estimated by eye, and direction was estimated using the boat's magnetic compass.

ENVIRONMENTAL DATA SUMMARY

Observing Unit ________ Date ________

TIME	SURFACE WIND				SWELL		WAVE		White Caps N: None S: Some M: Many	Sea Surface Temperature °C	REMARKS (Cloud cover, visibility, weather description, etc)
	Speed (Relative)	Direction from (deg M or R)	Ships Heading (if relative)	Nature (gusty, or steady, etc) (deg M)	Height (ft)	Direction from (deg M)	Height (ft)	Direction from (deg M)			

Figure 6. Sample Environmental Data Summary Form

2.3 DRIFTERS

The MTS drifters, designed and constructed at the R&DC, consisted of a waterproof box floated by polystyrene foam sandwiched between two pieces of plywood. An MTS transponder and batteries were contained in the waterproof box and were connected by flexible wave guides to the antenna on a pole that extended 4 feet (1.2 m) above the upper plywood surface. The drifters floated with the upper plywood surface awash (see Figure 7). A 15-pound (6.8 kg) concrete weight suspended from the four corners of the drifter provided sufficient stability so that the drifter antenna was observed to depart little from the vertical even in 4-foot (1.2 m) seas. A bicycle flag at the top of the pole made the drifter more visible to boaters and the monitor boat.

The MTS drifters were tested in the summer of 1982 for their ability to mark the water surface by deploying one or more drift cards next to them. Although the absolute motion of the MTS drifters and the drift cards was very similar, some relative motion was observed. In light winds, calm conditions, the drift cards traveled downwind from the drifter. In 15- to 20-knot (7.7 to 10.3 m/s) winds, 4-foot (1.2 m) seas, there was no appreciable difference in their motion. This difference in movement may be due to one or more of the following factors: (1) light winds move only the top few centimeters of the water, while in rough seas, turbulence smooths out the vertical gradient of the current for the top meter; or (2) in calm conditions, the drift card may be more exposed to the wind and be showing leeway, while in rough conditions, the card may be partly protected from the wind.

2.4 LIFE RAFTS

The three life rafts used in this experiment were circular commercial rafts with canopies and ballast systems. Two of the rafts were already at the R&DC and the third was purchased for this experiment. Section 2.4.1 discusses the general loading and states of the rafts. Sections 2.4.2 through 2.4.4 describe the rafts in the detail appropriate for this study. Except for identification, details not thought pertinent to leeway have been omitted for simplicity.

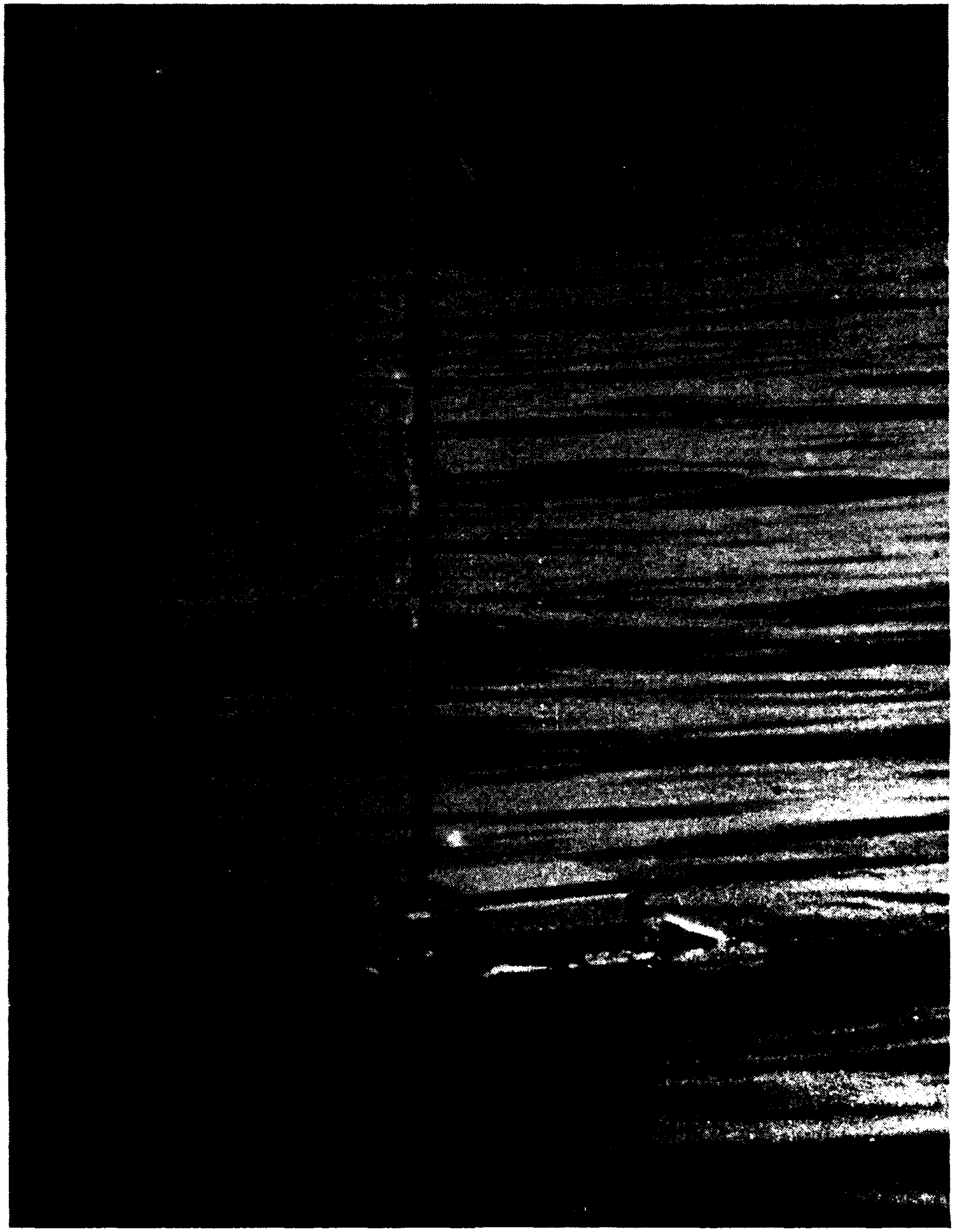


Figure 7. Deployed MTS Drifter

2.4.1 General Conditions

The three rafts were similarly deployed with the floor uninflated, without drogue, and empty except for approximately 80 to 100 pounds (36 to 45 kg) of equipment. The only difference in equipment was that the heaviest ballasted raft was not instrumented for wind due to the lack of time between receipt of and deployment of that raft. The weight of the wind instrument was 21 pounds (9.5 kg).

The change in draft of a circular raft due to changes in loading may be approximated by:

$$\text{Change in draft} = \frac{\text{Change in load}}{0.25\rho \Pi D^2}$$

where:

ρ = density of water (999.6 kg/m^3 or 62.4 lb/ft^3) and
D = diameter of raft.

Thus, for the rafts used in this experiment, the 100 pounds (45 kg) of equipment would increase the draft by 0.5 to 0.76 inches (1.3 to 1.8 cm). A full complement at 200 pounds (90 kg) per person would increase the draft by 5 to 6 inches (13 to 15 cm).

2.4.2 RFD 6-Man MK3A Life Raft

The RFD 6-Man Life Raft used was manufactured in 1976. The canopy was three equal sections (120 degrees each) with doors in two of the sections and a rain pouch in the third. The Meteorological Research, Inc., (MRI) mechanical weather station was mounted in a section where a door (not shown) would have been (see Figure 8). For the purpose of this test, only the door as shown open in Figure 8 is referred to as a door. The raft had two half-cylinder ballast bags. The bags were a full 5-inch (12.7 cm) half cyclinder for the central 20 inches (50.8 cm). The bags tapered flat to the end with the extra fabric pinched into a central fin. Ribs at both ends of the half cyclinder provided some rigidity. A loop of fabric, which would normally carry a gas cylinder for inflation was left hanging loose. The two boarding ladders that normally would be present were absent.

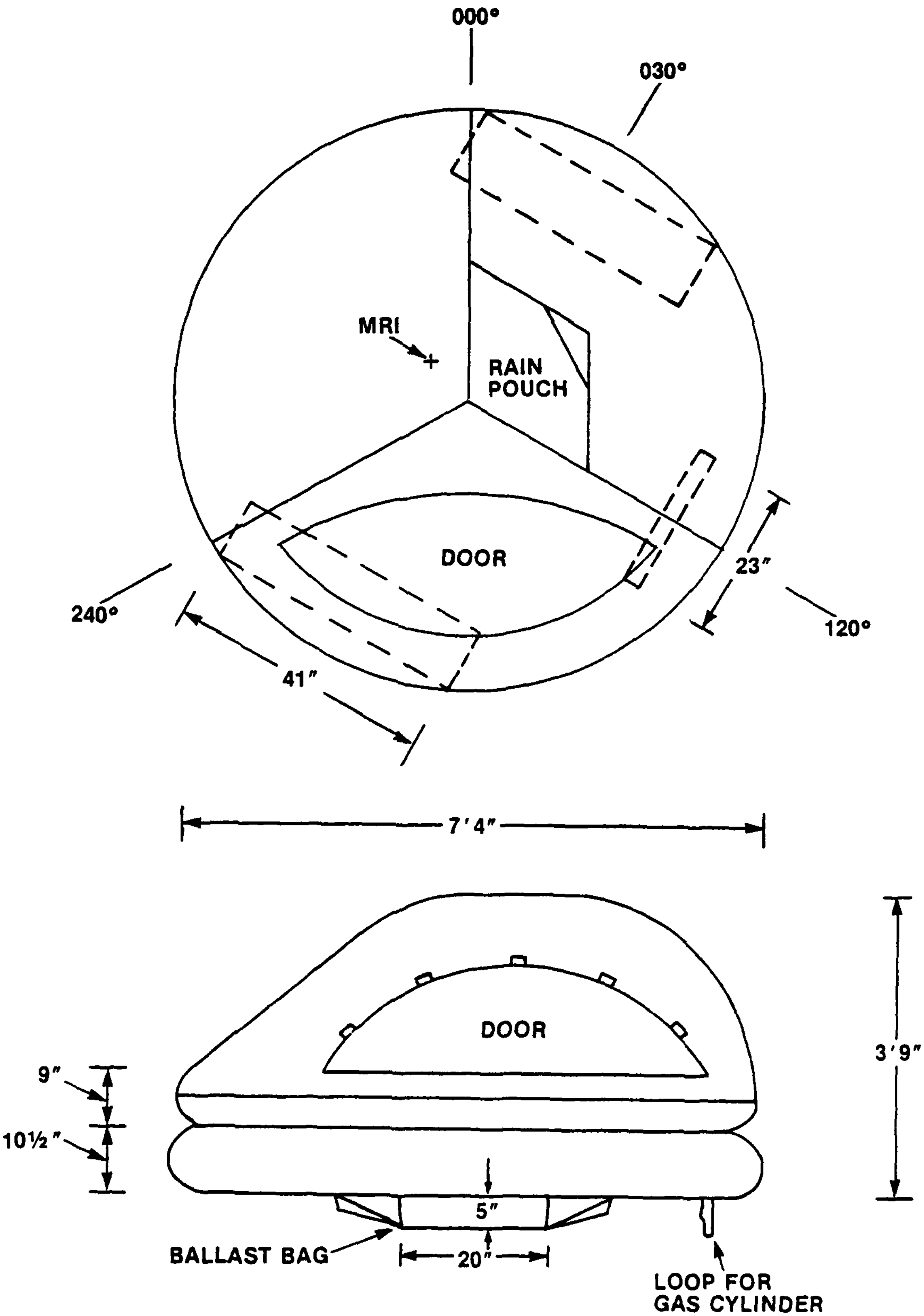


Figure 8. RFD 6-Man MK3A Life Raft

2.4.3 Switlik 4-Man Life Raft

The Switlik 4-Man Life Raft, serial number SPC/MM/36, manufactured on 26 September 1976, had a toroid ballast system. The raft had a T-shaped canopy with the door located at the head of the T (see Figure 9). The ballast toroid had a metal bar at the bottom of each section to aid in deploying and maintaining the bottom shape of the system. The toroid was divided into eight separate sections by baffles. A towing bridle (not shown in Figure 9) was attached to the raft by the door and hung down from the raft.

The raft used in the test had been damaged (most likely in handling) so that the baffles were blown; however, the author does not believe that this would have had any impact on leeway or the raft's behavior under the conditions encountered during this experiment.

2.4.4 Givens Buoy 6-Man Life Raft

The Givens Buoy 6-Man Life Raft was manufactured in 1983 for this experiment. It had a canopy constructed of three equal sections (see Figure 10) and a hemispheric ballast system. A towing bridle was located on the side of the raft containing the door. This raft was modified by Mr. Givens from the standard raft to include a deballasting slit in the bag opposite the towing bridle. The slit was closed by lacing and sealed by a flapper valve before deployment. The slit made recovery of the raft easier while reducing the risk of damage. It should not have affected the performance of the raft.

The MRI was not mounted on this raft; however, an MTS drifter was placed in the raft for tracking and the antenna pole extended out either the door or view port.

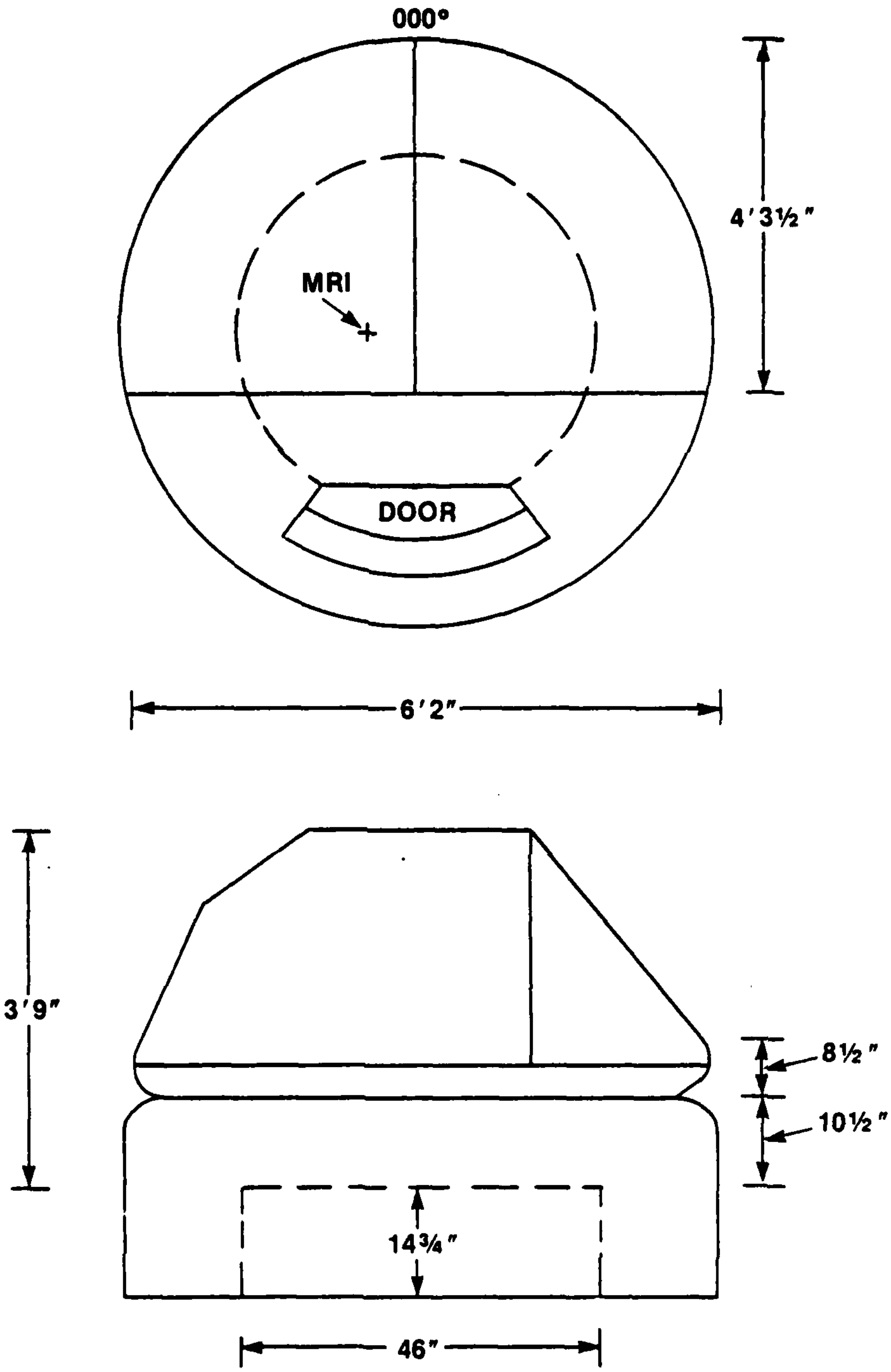


Figure 9. Switlik 4-Man Life Raft with Toroid Ballast

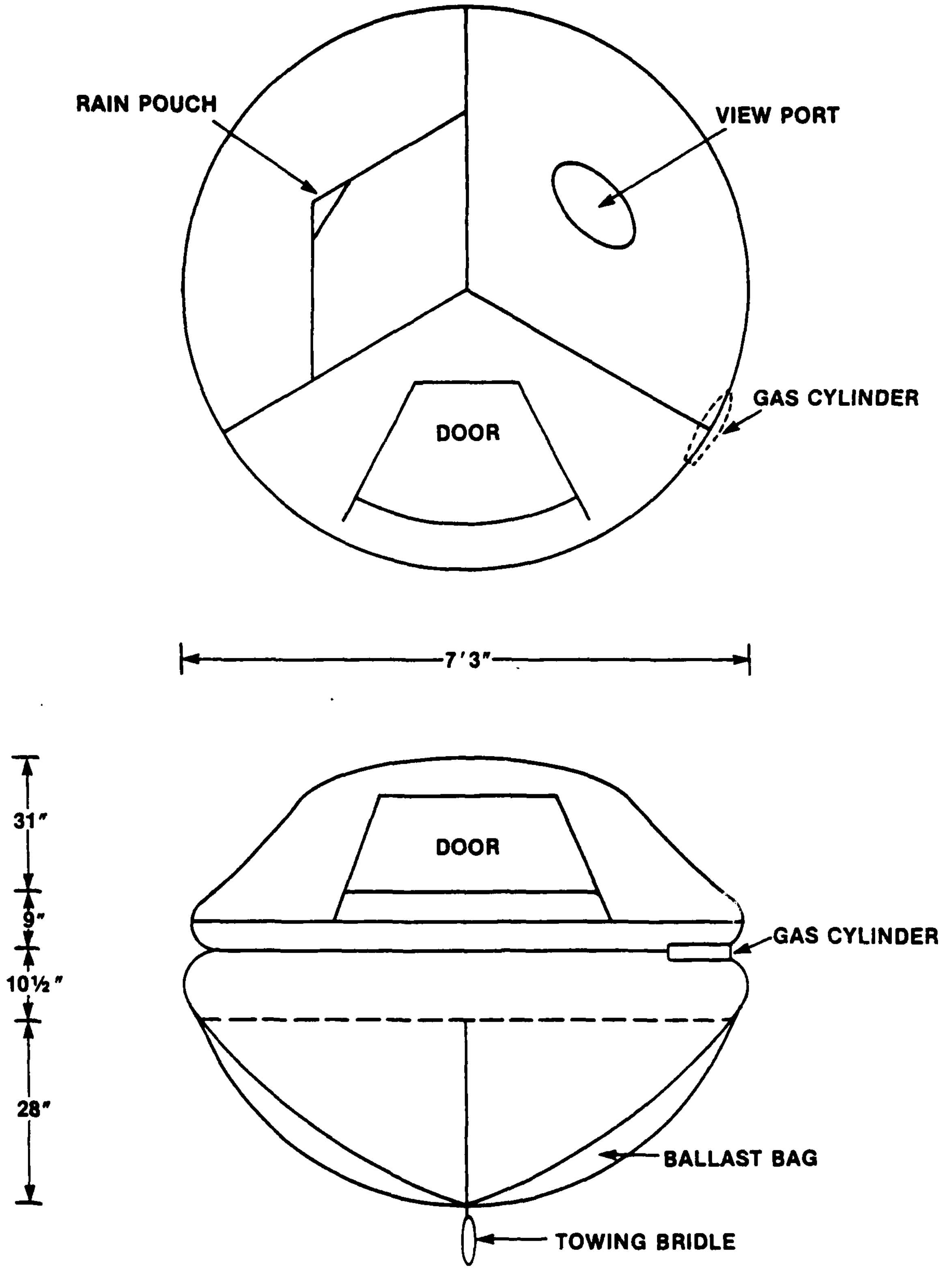


Figure 10. Givens Buoy 6-Man Life Raft

2.5 ENVIRONMENTAL CONDITIONS

The three critical environmental conditions are wind speed, wave height, and swell height. Data collection occurred in mild conditions; the wind was under 11 knots (5.6 m/s) with waves of 0 to 2 feet and swells up to 4 feet (1.2 m). Because of the antenna height of the drifters, data could not be collected in seas greater than 4 feet (1.2 m). Table 4 presents the environmental conditions for the data collection for each of the rafts. The RFD 6-Man Life Raft was tested in two configurations: door open and door closed. The Switlik and Givens life rafts were tested in only one configuration: door closed.

TABLE 4

RANGE OF ENVIRONMENTAL CONDITIONS FOR WHICH DATA WERE COLLECTED FOR EACH RAFT

RAFT	WIND SPEED*	WAVE HEIGHT†	SWELL HEIGHT†
RFD			
Door closed	2.3-6.5 (1.2-3.5)	0-0.5 (0-0.2)	0-3 (0-0.9)
Door opened	4.7-10.4 (2.5-5.4)	1-2 (0.3-0.6)	0-0.5 (0-0.2)
SWITLIK			
Door closed	2.8-10.4 (1.4-5.4)	0-1 (0-0.3)	0-3 (0-0.09)
GIVENS			
Door closed	3.8-11.0 (1.9-5.6)	0-2 (0-0.6)	0-4 (0-1.2)

* Values in parentheses are in meters/second (m/s). All others are in knots.

† Values in parentheses are in meters (m). All others are in feet.

CHAPTER 3
DATA REDUCTION

3.1 INTRODUCTION

The process of preparing the collected data for analysis is discussed in this chapter. The process is one of removing all effects of the current from the raft's motion. Conceptually, the raft is then being driven by the wind through a currentless ocean. Leeway and "effective" wind are the raft's velocity and apparent wind as observed from a point moving with the current.

For the first step of the process, the raw data was screened subjectively for bad data, and then made suitable for velocity calculations by a four-point piecewise linear interpolation scheme (Section 3.2). Next, the 4-minute averaged surface current at the raft was estimated from the array of drifters (Section 3.3). This current was vectorally subtracted from the raft's velocity and true wind to calculate leeway and "effective" wind, respectively (Section 3.4).

3.2 DATA PREPARATION

The wind records and position records were checked subjectively for glitches in the data. Glitches in the wind data showed up as unrealistic wind speeds such as 90 knots (46 m/s) or sudden large changes in the heading of the wind station. The position record was edited for bad positions causing unrealistic courses and speeds. The beginning and end of each drift record were checked for contamination from the movement of the monitor boat.

Next, the individual drift records were processed through a piecewise linear interpolation scheme to produce a record consisting of evenly temporally spaced positions. This was necessary for velocity calculations, and served to filter out the high frequency small-scale perturbations due to the MTS. The scheme involved the interpolation of a new position (x, y, time) at 2-minute intervals from a least squares

regression of x as a function of time and of y as a function of time using four data points for the regression. Any gap in a drift record longer than 7 minutes caused the routine to mark the end of one drift interval and the start of another.

3.3 ESTIMATION OF SURFACE CURRENT

The one parameter not measured that is essential for determination of leeway is the current at the raft. That parameter is estimated from the drifter array. The planned method of estimating the current was the method of weighted averages, but that method proved to be inadequate (Section 3.3.1). A piecewise regression method was selected and is discussed in Section 3.3.2.

3.3.1 Weighted Averaging

Several methods of averaging were tried and discarded. A straightforward simple average was ruled out as it allowed distant drifters too much influence on the average value. The first method tried was a weighted average where the weighting function was the inverse distance between each drifter and the raft. The average current was calculated from:

$$\bar{C} = \frac{\sum_{i=1}^{N} \frac{C_i}{X_i}}{\sum_{i=1}^{N} \frac{1}{X_i}}$$

where:

$\bar{C}$ = the average current,

C_i = current from drifter (i),

X = distance between drifter (i) and the raft, and

N = number of drifters.

This method was tested by predicting the current at several drifters in the array using the remaining drifters. The method was discarded when it failed to handle the velocity gradients present in the data. Raising the inverse distance to several powers up to the fourth did not solve this problem. The weighted averaging failed because it:

1. Generalized a two (or three) dimensional problem into a one-dimensional problem, and
2. Failed to provide any check on the accuracy of the prediction.

3.3.2 Piecewise Regression

The wind and position records were compiled into one record using a time step of 4 minutes. All drifters' velocities were calculated centered in time; thus, the U-component of velocity at time = t_0 was computed using the x component of position at t_0 + 2 minutes minus x at t_0 - 2 minutes:

$$U_t = \frac{X_{t+2} - X_{t-2}}{4 \text{ minutes}} \quad .$$

The wind was averaged over the 4-minute interval from t - 2 to t + 2. The current at the test craft was estimated from U and V velocity surfaces fitted to the array for each 4-minute interval. The velocity surfaces were constructed by the summation of independent regressions using the following variables: X, Y, X^2, Y^2, X^3, and Y^3. The single variable giving the best fit as determined by the method of least squares was selected. The predicted velocity field from the regression was subtracted from the observed velocity field leaving a residual. From the remaining variables, a regression using the single variable giving the best fit to the residual was done. The second regression was added to the first and a second residual field was calculated. This procedure was repeated until all of the variables were used or there was no further reduction in the residual field. The surface current at the raft was estimated from the regression, only if the regression passed two tests. The first test was that, for each drifter, the difference between the predicted and actual velocities must be less than or equal to 0.04 knots (2 cm/sec). If not, the regression and test would be repeated excluding any drifter more than 875 yards (800 m) from the raft. A second failure caused the data to be excluded, and the routine proceeded to the next time interval. The second test was that the raft was within the drifter array used in the regression. If all of the drifters used in the regression were within a 170-degree sector from the raft, the data was excluded.

3.4 COLLATION AND LEEWAY CALCULATION

The estimated surface current record was screened for inconsistent velocity changes. Next, the primary and secondary effects of the current were removed from the data. The primary effect is the current-induced drift of the raft. This was removed by vectorally subtracting the current from the raft's motion leaving only the leeway.

The secondary effect is that of the current-induced drift of the raft changing the wind effectively acting on the raft. For a 2-knot (1 m/s) current moving in the same direction as a 7-knot (3.6 m/s) wind, the raft has an effective wind of 5 knots (2.6 m/s). With the wind opposing the current, the opponent wind is 9 knots (4.6 m/s). For a raft with a leeway of 6 percent of the wind, this can result in a difference in leeway of 0.24 knots (12 cm/s) between the two cases. The same wind and current, if orthogonal, would result in the effective wind being 15 degrees off the true wind.

After the current was vectorally subtracted from the wind, all the data for one day was collated into one record. Then the data was screened subjectively for inconsistencies between the monitor boat and wind station wind records, and the raft's wind and leeway records.

CHAPTER 4
ANALYSIS

Leeway (speed and angle) is a function of the environmental loading on a craft and the craft's configuration and orientation to the environmental loading. This analysis is based on the premise that any change in leeway for a particular craft must be due to a change in either the environmental loading or the craft's orientation. All other apparent changes in leeway are due either to errors in measurement or to the forces not being in equilibrium.

Section 4.1 discusses the relationship between a raft's configuration and its orientation to the environmental loading, and the general effect of this relationship on leeway.

Section 4.2 deals with a specific analysis of leeway angle as a function of wind speed and the relative wind angle.

4.1 RAFT'S ORIENTATION TO WIND

A craft whose windage or keel areas are not symmetric to a vertical line drawn through the center of the craft will have preferred orientations to the environmental loading. The craft will be unable to maintain other orientations passively. A common example is a disabled ship riding in the trough of the waves. Depending on the craft's configuration, a change in orientation can cause different leeway characteristics to be displayed.

The main environmental loading element in this experiment was the wind. The relative wind was monitored on board the RFD 6-man and Switlik 4-man life rafts to determine any changes in the rafts' orientation to the wind. The RFD life raft has two half-cylindrical ballast bags and a canopy divided into three equal sectors. The Switlik life raft has a toroid ballast system and a T-shaped canopy. The effects of orientation for the RFD and the Switlik life rafts are discussed in Sections 4.1.1 and 4.1.2, respectively.

4.1.1 RFD 6-Man MK3A Life Raft

The RFD life raft was the only raft tested whose plane of symmetry was dictated by its bottom geometry. The vertical plane of symmetry divides the raft along a line from 120 through 300 degrees relative (° R) (see Figure 11). The door and the wind instrument (MRI) bear approximately 180° R and 310° R from the raft's center. The major features of the raft's bottom are the two half-cylinder ballast bags (030° R and 210° R) and the holder for the compressed gas cylinder (120° R).

The RFD life raft was tested with the door closed for the first two days and open on the third. With the door closed, the raft kept the relative wind from 030 to 050° R. With the door open, the raft initially kept the relative wind from 030 to 045° R. Only after the raft was turned by the monitor boat so the open door was to windward did the raft assume and maintain the orientation of the relative wind from 190 to 235° R.

The relative wind direction was very stable. During the three days of testing, the raft changed the sector of canopy to windward only once without interference. The raft spun completely around with the door closed and resumed its original orientation.

The orientation of the raft to the wind had a dramatic influence on the leeway angle (see Figure 12). The RFD raft went to the right of downwind (positive leeway angle) with a relative wind of 030 to 050° R and went to the left of downwind with a relative wind from 190 to 235° R. The orientation of the ballast bags suggests that the RFD raft would have zero leeway angle with an aspect of 300° R to the wind.

The effects of configuration and orientation on leeway speed are not as obvious. e data presented in Figure 13 suggests that the RFD life raft has a lower leeway speed en the door is open, especially when the wind is blowing into the open door; however, a clusion should not be made from a single open-door drift under wind conditions that e different than those for the rest of the test period.

The reasons for the preferred orientations of the raft to the wind hold the key to icting the raft's leeway behavior. The location of the compressed gas cylinder r (and wind instrument) probably made the orientation of 300° R to windward

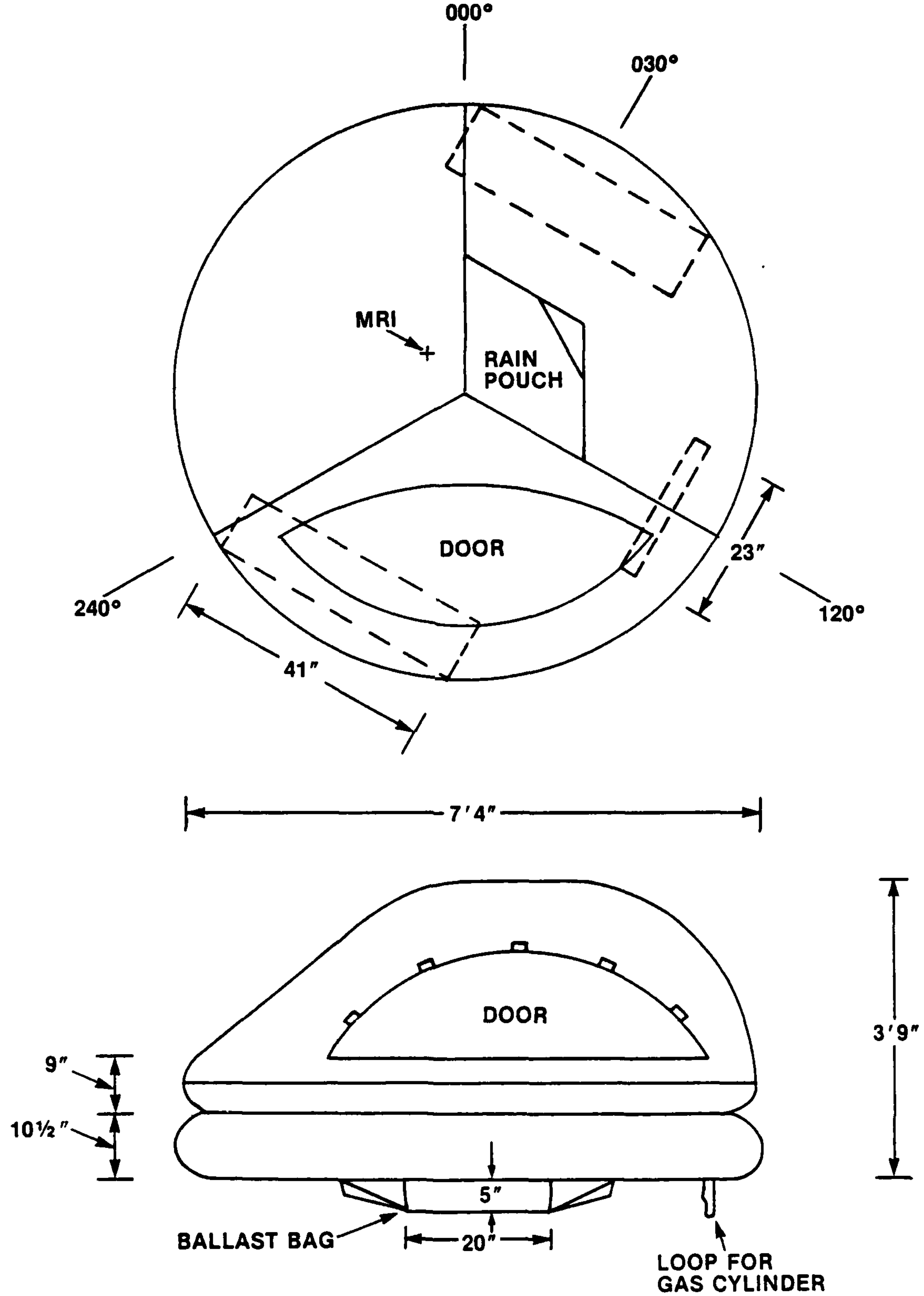
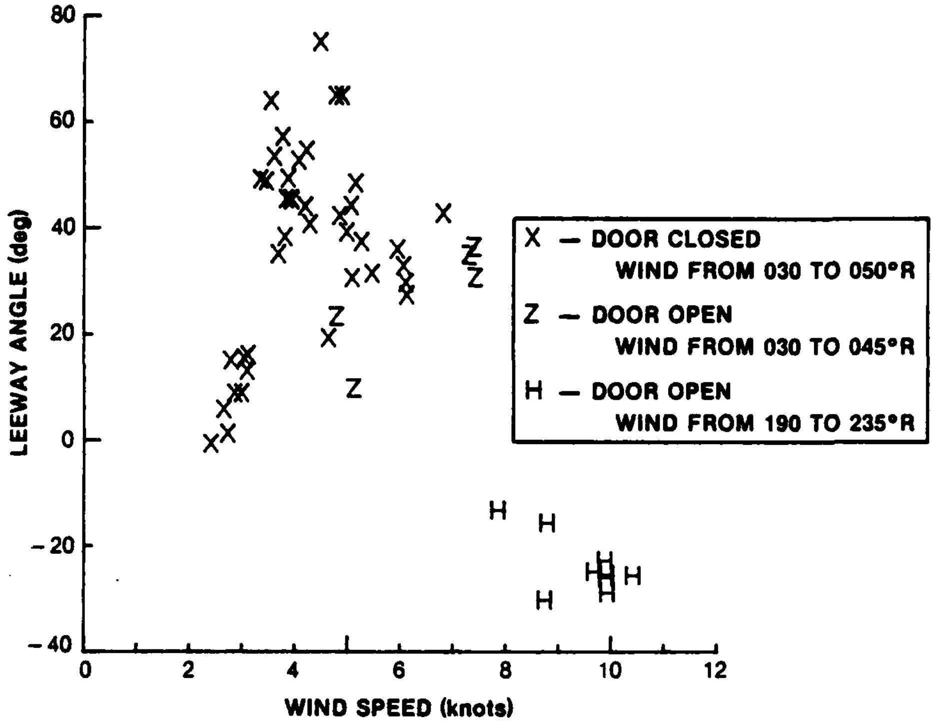


Figure 11. RFD 6-Man MK3A Life Raft



NOTE: POSITIVE LEEWAY ANGLE DENOTES THE RAFT IS DEFLECTED TO THE RIGHT OF DOWNWIND.

Figure 12. Leeway Angle for Different Orientations and Configurations of RFD 6-Man MK3A Life Raft

unstable. The reason that the orientation of 180°R to windward was unstable with the door closed could be that the closed door made the canopy's fabric in that section tighter or that the instability is an artifact of the deployment method.

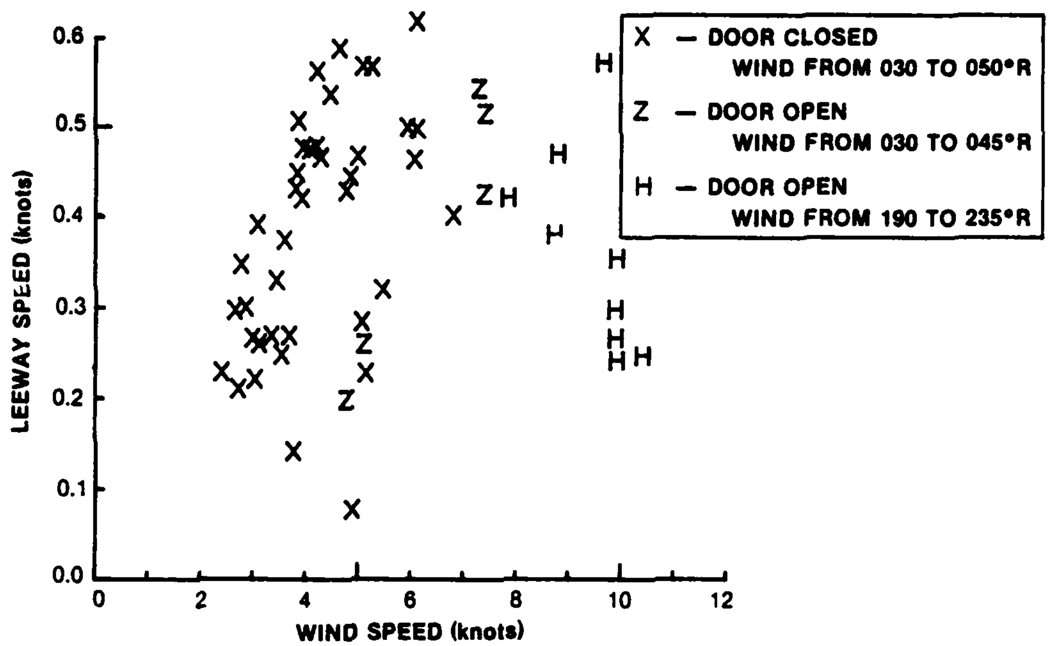


Figure 13. Leeway Speed for Different Orientations and Configurations of RFD 6-Man MK3A Life Raft

4.1.2 Switlik 4-Man Life Raft

The T-shaped canopy of the Switlik life raft permits a single vertical plane of symmetry lying along the stem of the "T" and bisecting the door, located at the cross of the "T" (see Figure 14). The underwater portion of the raft, mainly the toroid ballast system, is symmetric to a vertical axis through the center of the raft, except for the towing bridle located below the door.

In 5 days of testing, the sector of the canopy to windward changed 28 times without any apparent effect on leeway. The Switlik raft's sensitivity to perturbations in the wind may be due to the axial symmetry of the toroid ballast system; however, the preferred orientations suggest that the data is biased (see Figure 15). The distribution of stable relative wind directions is skewed approximately 20 degrees counterclockwise relative to the plane of symmetry. While the relative wind was stable 14 times in the

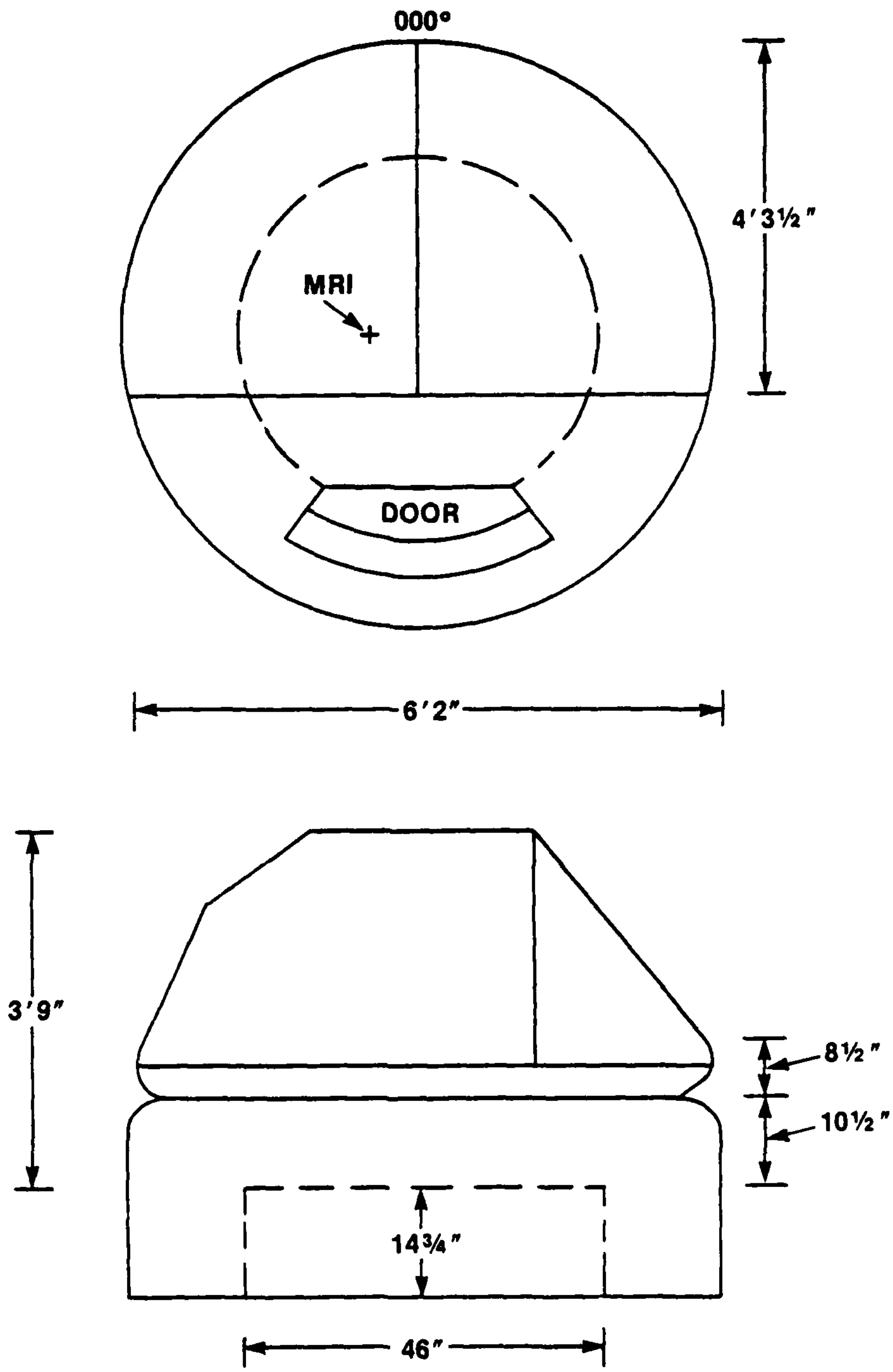


Figure 14. Switlik 4-Man Life Raft with Toroid Ballast

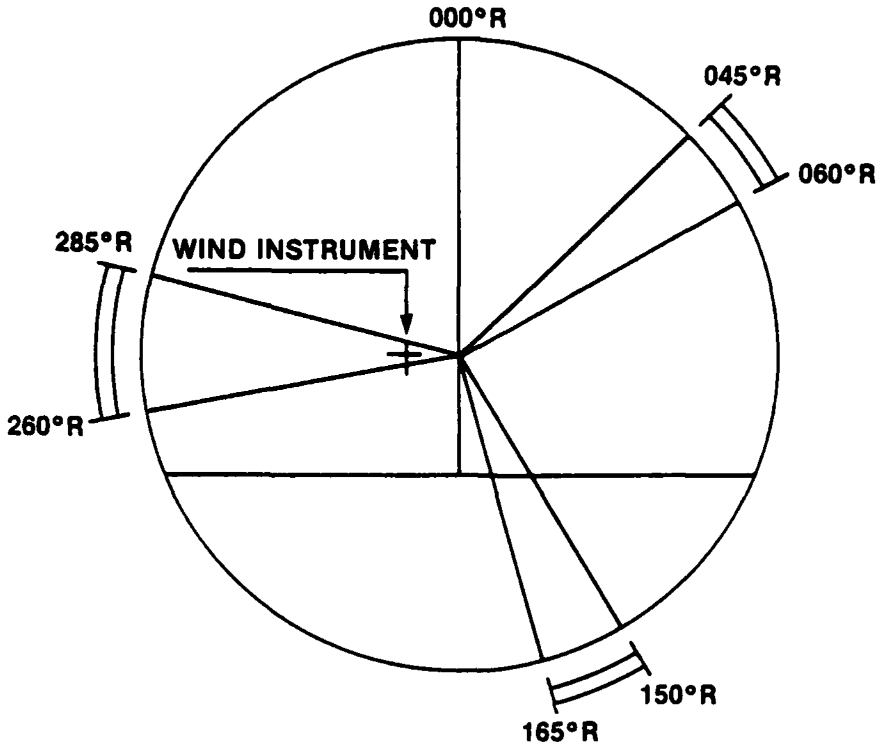


Figure 15. Distribution of Relative Wind Angles for Switlik 4-Man Life Raft

045 to 060°R sector and 11 times in the 150 to 165°R sector, it was stable in the 260 to 285°R sector only 3 times. This suggests that the increased drag from the wind sensor is affecting the behavior of the raft.

4.2 LEEWAY ANGLE

Leeway angle is the angle between the direction of the wind-induced motion of a craft and downwind. The convention used in this report is that the leeway angle is positive to the right and negative to the left of downwind.

In this section, leeway angle is studied in relation to the relative wind direction and the configuration of the RFD 6-man and the Switlik 4-man rafts. The concept behind this section is that leeway angle is a function of the relative wind direction and the configuration of the craft. Any change in leeway angle not accompanied by a change in the relative wind direction or configuration must be due to errors in measurement. The distribution of leeway angles by raft are presented in Table 5.

TABLE 5

DISTRIBUTION OF LEEWAY ANGLES BY RAFT

LIFE RAFT	RANGE OF LEEWAY ANGLES (deg)
Switlik 4-Man	-43 to 45
Givens 6-Man	-29 to 49
RFD 6-Man (all)	-30 to 75
Door closed	-0.7 to 75
Door open	-30 to 36
NOTE: Positive indicates leeway angle to right of downwind; negative indicates leeway angle to left of downwind.	

4.2.1 Leeway Angle for RFD 6-Man MK3A Life Raft with Door Closed

The difference in leeway due to general orientation and to the door being closed or open are discussed in Section 4.1.1. With the door closed, only one sector of the canopy was to windward. The leeway angle ranged from -0.7 degrees to +75 degrees with wind speeds of 2.3 to 6.5 knots (1.3 to 3.5 m/s). The relative wind direction ranged from 030°R to 050°R.

This discussion demonstrates a systematic analysis of the physical reasons for leeway angle. The method of least squares regression used in this analysis is strictly statistical and cannot fully model the physical relationship of leeway angle to the relative wind (see Table 6). A level of significance (α) as determined from the method of analysis of variance of 0.05 or less is considered to be meaningful. Equation 4 is derived by substituting Equation 1 into Equation 2. The only purpose for Equation 4 is to show that the regression for Equations 1, 2, and 3 are consistent because of the similarity of Equations 3 and 4 (see Table 6).

TABLE 6

RESULTS OF LINEAR LEAST SQUARES REGRESSION ANALYSIS
OF LEEWAY ANGLES FOR RFD 6-MAN MK3A LIFE RAFT WITH DOOR CLOSED

EQUATION NUMBER	EQUATION	NUMBER OF OBSERVATIONS (N)	CORRELATION COEFFICIENT (r)	LEVEL OF SIGNIFICANCE (α)
1	Rwd (deg) = 14.4499 + 5.8800(W)	37	0.82	0.001
2	La (deg) = -1.9694 + 1.0122(Rwd)	37	0.43	0.01
3	La (deg) = 10.04575 + 6.2351(W)	40	0.37	0.025
4	La (deg) = 12.66 + 5.9517(W)	-		-

Rwd = Relative wind direction in degrees, W=Wind speed,
W = Wind speed,
La = Leeway angle in degrees,

The ballast bags on the raft act like a keel. The keel may be visualized as running along the axis of least resistance, which is perpendicular to a line passing through the centers of the raft and of each ballast bag (see Figure 16). The angle at which the water strikes the acute angle between the axis of least resistance and the direction of drift (resistance angle) can be computed in this case by:

$$\text{Resistance angle (Ra) (degrees)} = 300^\circ - (\text{Rwd}+\text{La}+180^\circ) .$$

Table 7 shows a comparison of the results of wind speed calculations using the equations given in Table 6. In Table 7, it can be seen that the relative wind direction and leeway angle are proportional to wind speed. As the wind speed increases, the drag on the ballast bags will increase as the leeway increases (drag generally increases as the square or cube of the velocity). At higher leeway speed, the effect of drag on the bags increases; thus, the resistance angle decreases. However, the linear model is limited. A truly good model must allow for the following:

1. Resistance angle approaches 0 asymptotically as the wind speed increases,

2. Leeway angle must always be less than 90 degrees.

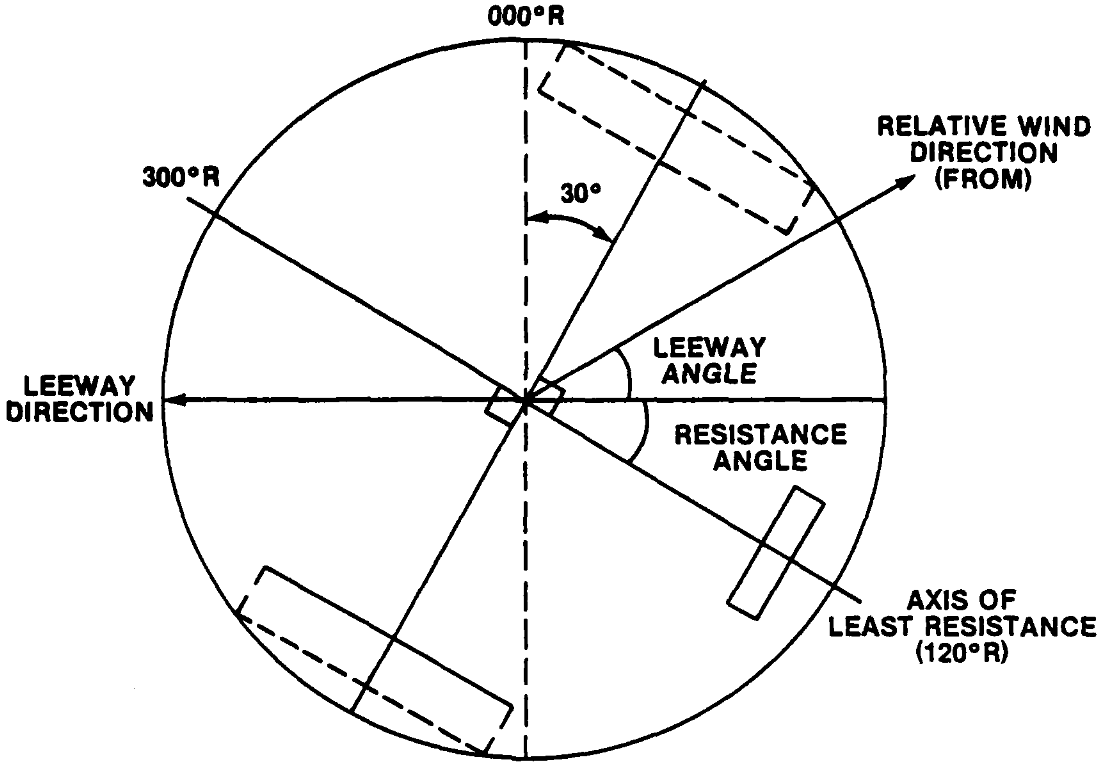


Figure 16. Wind and Leeway Geometry of RFD Mk3A 6-Man Life Raft

TABLE 7

COMPARISON OF WIND SPEED CALCULATIONS USING EQUATIONS IN TABLE 6

WIND SPEED W (knots)	RELATIVE WIND Rwd (Eq. 1) (deg)	LEEWAY ANGLE La (Eq. 3) (deg)	LEEWAY ANGLE La (Eq. 4) (deg)	RESISTANCE ANGLE Ra (deg)
3	32.1	29.2	30.5	58.7
5	43.8	41.6	42.4	34.5
7	55.6	54.1	54.3	10.3
9	67.4	66.6	66.2	-13.9
11	79.1	79.0	78.1	-38.2

4.2.2 Leeway Angle for Switlik 4-Man Life Raft

This analysis differs from the analysis in the previous section in that the data considers relative wind directions over two sectors of the canopy vice one sector. The sectors are defined by the canopy support tubes. This was done because the relative wind direction data for a given sector did not vary with wind speed.

The results of a least squares analysis of leeway angle, relative wind direction, and wind speed are presented in Table 8. The data is for wind speeds of 2.8 to 10.4 knots (1.4 to 5.4 m/s). A level of significance as determined from the method of analysis of variance of 0.05 or less is considered to be meaningful. Equation 4 is derived from Equations 1 and 2 as in Section 4.2.1. The difference between Equations 3 and 4 demonstrates that the set of regression equations is not valid, even though the individual equations are statistically significant. Equation 1 is significant because the relative wind directions of 150°R and 160°R occurred only at wind speeds above 7 knots. It is meaningless as the relative wind direction of 050°R occurred throughout the range of wind speeds. (There is no leeway data corresponding to the relative wind directions of 260°R to 285°R.)

For a relative wind direction of 050°R, the leeway angle ranged from -29 degrees (left of down wind) to +45 degrees (right of down wind). For relative wind directions of 150°R and 160°R, the leeway angles ranged from -45 degrees to +6 degrees. Thus, there is considerable overlap of leeway angles with regard to relative wind direction.

The bottom geometry of the Switlik life raft is symmetric to a vertical line through the raft's center. The only asymmetry is the towing bridle by the raft's door. If the towing bridle causes the leeway angles, its location relative to the wind would determine the sign of the leeway angle. The towing bridle was to the left of down wind for both sets of relative wind directions. Therefore, the leeway angles due to the towing bridle would be negative. The relative wind directions would change with increasing wind speeds because the effect of the towing bridle would increase with higher leeway speeds. None of this was observed. Therefore, the leeway angles must be due to the uncertainty in determining the current, the raft's velocity, and the wind. These ostensible leeway angles would disappear if measured over a time interval of several hours.

TABLE 8

RESULTS OF LINEAR LEAST SQUARES REGRESSION ANALYSIS OF LEEWAY ANGLES FOR SWITLIK 4-MAN LIFE RAFT

EQUATION NUMBER	EQUATION	NUMBER OF OBSERVATIONS (N)	CORRELATION COEFFICIENT (r)	LEVEL OF SIGNIFICANCE (α)
1	Rwd (deg) = 1.0337 + 11.0633(W)	37	0.49	0.005
2	La (deg) = 7.2544 - 0.1655(Rwd)	37	0.36	0.05
3	La (deg) = 20.28925 - 3.3993(W)	42	0.33	0.05
4	La (deg) = 7.0833 - 11.2289(W)	n/a		n/a

Rwd = Relative wind direction in degrees
W = Wind speed
La = Leeway angle in degrees

4.3 EFFECT OF RAFT DESIGN ON LEEWAY

The three rafts used in this experiment can be categorized by the shape of the canopy, the type of ballast system, or the personnel complement. For the purpose of this discussion, the rafts are categorized by the symmetry of the underwater portion or hull. A hull that is symmetric to a vertical line through the center of the raft is considered symmetric. All others are considered asymmetric, even if there exists a single horizontal line of symmetry. Items such as towing bridles shown to have negligible effects on leeway are not considered in categorization. Thus, the symmetric rafts are the Switlik 4-man and the Givens 6-man life rafts. The RFD 6-man life raft is asymmetric.

Sections 4.1 and 4.2 demonstrate that the RFD and the Switlik possessed different leeway characteristics. The leeway angle for the RFD was correlated to the relative wind direction. For a given sector of the RFD's canopy, the relative wind direction was correlated to the wind speed. The leeway angles for the Switlik were not correlated on the relative wind direction. For the Switlik, the relative wind direction could not be correlated to the wind speed. The Switlik changed the sector of the canopy to windward much more frequently than did the RFD. The reason for all of the above lies in whether the hull is symmetric or asymmetric.

A symmetric raft is similar in concept to a ball floating in the water. The symmetric underwater portion moving through the water produces only drag aligned with the motion of the raft. There is no force to counteract any net moment due to the wind. There is no realistic mechanism for the raft to move off the downwind direction. Any net moment due to the wind will cause the raft to spin. Thus, the relative wind direction is determined so there is no net moment by the force of the wind.

An asymmetric raft is similar in concept to a sailboat. A sailboat is able to sail off the wind because its keel acts in a manner similar to an aircraft wing. As it cuts through the water, it produces two orthogonal components of force: drag and lift. The drag component is aligned with the direction of the craft, while the lift component is perpendicular to it. Except in rare cases, the creation of lift is accompanied by a moment (torque). The raft spins unless this moment is offset by an opposing moment caused by the wind. The lift component allows the sailboat and asymmetric raft to sail off the downwind direction. The magnitudes of the individual forces and moments change with the wind velocity and the leeway velocity. Thus, the leeway angle and relative wind direction must change to maintain the balance of forces and moments.

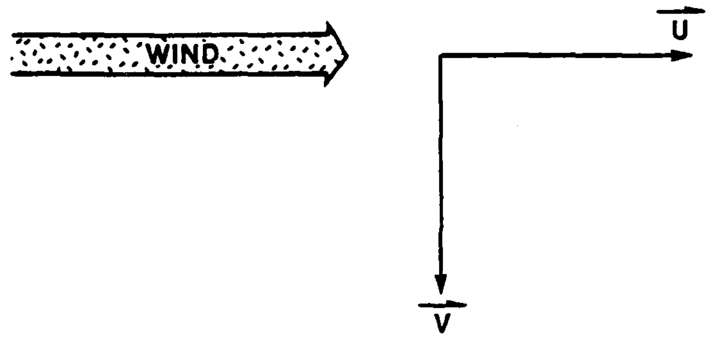
On a real raft, towing bridles or construction details prevent the underwater portion from being perfectly symmetric. The effect of these items can be expected to be negligible at low leeway speeds. Based on the above discussion, the Givens 6-man raft can be expected to behave in a similar manner to the Switlik 4-man raft. Both rafts should have small, if any, true leeway angles, and can be expected to change their orientation to the wind frequently.

4.4 LEEWAY SPEED

The leeway speed and wind speed data are 4-minute averages relative to the current of the upper 3 feet (1 m) of the ocean. Another way to study leeway speed is to consider leeway rate. Leeway rate is the ratio of leeway speed to wind speed.

The methods of multiple linear regression and stepwise regression were tried to relate leeway to wind speed, and height and direction of waves and swells. Orthogonal coordinates were assigned with one component assigned on the along-wind direction and

the other coordinate assigned perpendicular to the wind and positive to the right as shown below:



None of the regressions were significant improvements over the linear least squares regression of leeway speed and wind speed. Therefore, the results of that analysis are not presented in this report.

4.4.1 Leeway Speed versus Wind Speed

Leeway speed versus wind speed for the RFD, Switlik, and Givens life rafts are plotted in Figure 17. Considerable scatter in the data can be seen. The lightly ballasted RFD raft drifted faster than the deeper draft Switlik and Givens rafts. Due to the limited amount of data on the RFD life raft with the door open, all analysis of leeway speed for the RFD raft will be with the door closed.

The regression equations of leeway speed to wind speed are presented in Table 9. The F-statistic is the ratio of the variance explained by the regression to the variance left unexplained. P is the probability of making an error by accepting the regression when leeway rate and wind speed are independent. All three equations are significant at the 0.05 level ($P < 0.05$). The low correlation coefficients are due to the scatter in the data and limited range of wind speeds (see Figures 18, 19, and 20). The standard error of estimate (Sy.x) gives the scatter of the data around the regression line in that approximately 68 percent and 95 percent of the leeway data lies within one and two Sy.x, respectively, of the regression line.

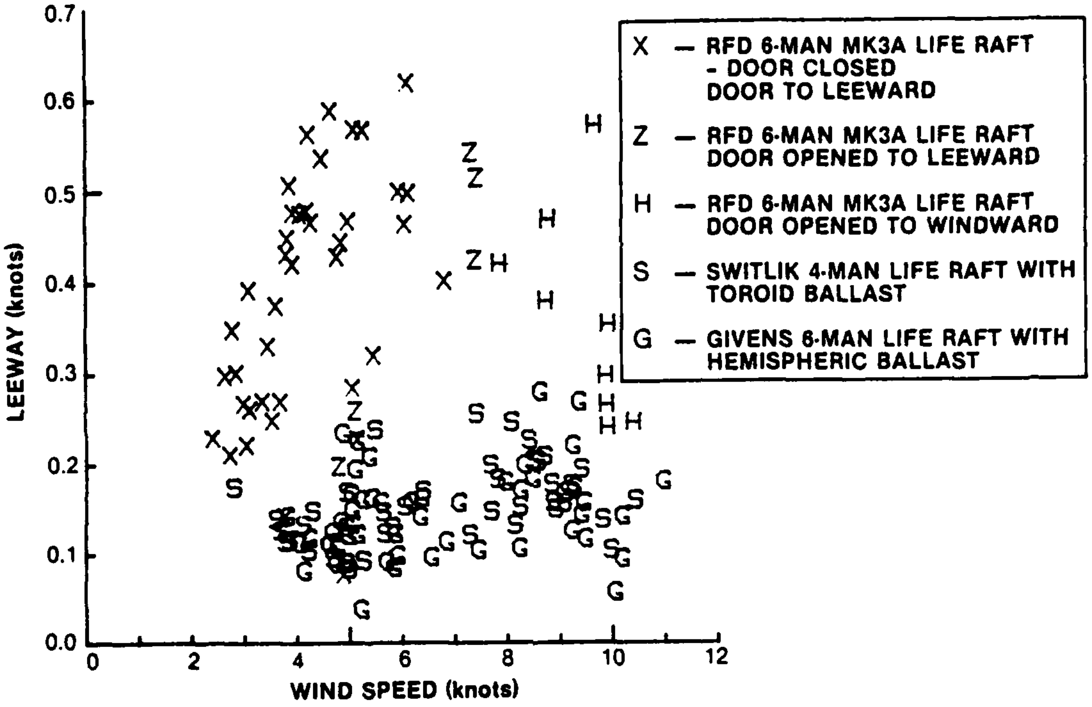


Figure 17. Leeway Speed versus Wind Speed for All Three Life Rafts

The 90-percent confidence limits of the regression equation presented in Figures 18, 19, and 20 were calculated using the following equation (Snedecor and Cochran, 1980):

$$Y = a + bX \pm \sqrt{2F_{0.1}} \times S_{y.x}\sqrt{\frac{1}{n} + \frac{X^2}{\sum_{i=1}^{n} x_i^2}}$$

where:

Y = Leeway speed (predicted),

X = Wind speed (particular),

$F_{0.1}$ = F-statistic for level of significance of 0.1,

$S_{y.x}$ = Standard error of estimates,

n = Number of data points, and

$\sum_{i=1}^{n} x_i^2$ = Sum of the squares of all wind speeds in the data.

TABLE 9

RESULTS OF LINEAR LEAST SQUARES REGRESSION AND ANALYSIS OF VARIANCE OF LEEWAY SPEED (L) TO WIND SPEED (W)

LIFE RAFT	NUMBER OF DATA POINTS	LEEWAY SPEED L = a + bW	90-PERCENT CONFIDENCE LIMITS		CORRELATION COEFFICIENT (r)	STANDARD ERROR OF ESTIMATE (Sy.x)	DOF*		F-STATISTIC	PROBABILITY† (P)
			a	b			REG	RES		
RFD 6-man (Door closed)	40	0.145 + 0.0568W (0.075 + 0.0568W)	0.020 0.271 (0.010) (0.139)	0.0281 0.0856	0.48	0.118 (0.061)	1	38	11.12	0.001 < P < 0.005
Switlik 4-man	42	0.100 + 0.0083W (0.051 + 0.0083W)	0.065 0.134 (0.034) (0.069)	0.0035 0.0132	0.42	0.040 (0.020)	1	40	8.36	0.005 < P < 0.01
Givens 6-man	48	0.100 + 0.0064W (0.051 + 0.0064W)	0.062 0.137 (0.032) (0.070)	0.0012 0.0117	0.29	0.044 (0.023)	1	46	4.19	0.025 < P < 0.05

NOTE: Values and equations in parentheses are for meters/second (m/s) if different. All others are in knots.

* DOF = degrees of freedom; REG = regression; RES = residual

† Probability of making an error by accepting the regression when leeway speed and wind speed are independent.

The regression for the RFD life raft (door closed) agrees quite well with the SAR Manual recommendation (see Figure 18). The regressions for the Switlik and the Givens life rafts do not agree with the SAR Manual recommendation for canopied rafts with deep-draft ballast systems (see Figures 19 and 20). The reason for agreement and disagreement may lie with the thickness of the water layer to which the leeway is relative. The SAR Manual recommendation for canopied life rafts with ballast bags for wind speeds of 5 knots and greater is from data using a dye patch as a current marker (Hufford and Broida, 1974). The dye patch would mark a thickness of water close to that marked by the MTS drifters [3 feet (1 m)]. The SAR Manual recommendation for the canopied rafts with deep-draft ballast systems is based on data using a buoy with a 10-foot (3-m) square window-shade drogue (Scobie and Thompson, 1979). The much thicker layer, as marked by the drogue buoy, may be slower than the thinner layer marked by a dye patch or MTS drifter. Another possible explanation is that Scobie and Thompson (1979) had seas of 5 to 15 feet (1.5 to 4.6 m), while the Summer 1983 data was obtained when the maximum waves were 2 feet (0.6 m) and the maximum swells were 4 feet (1.2 m).

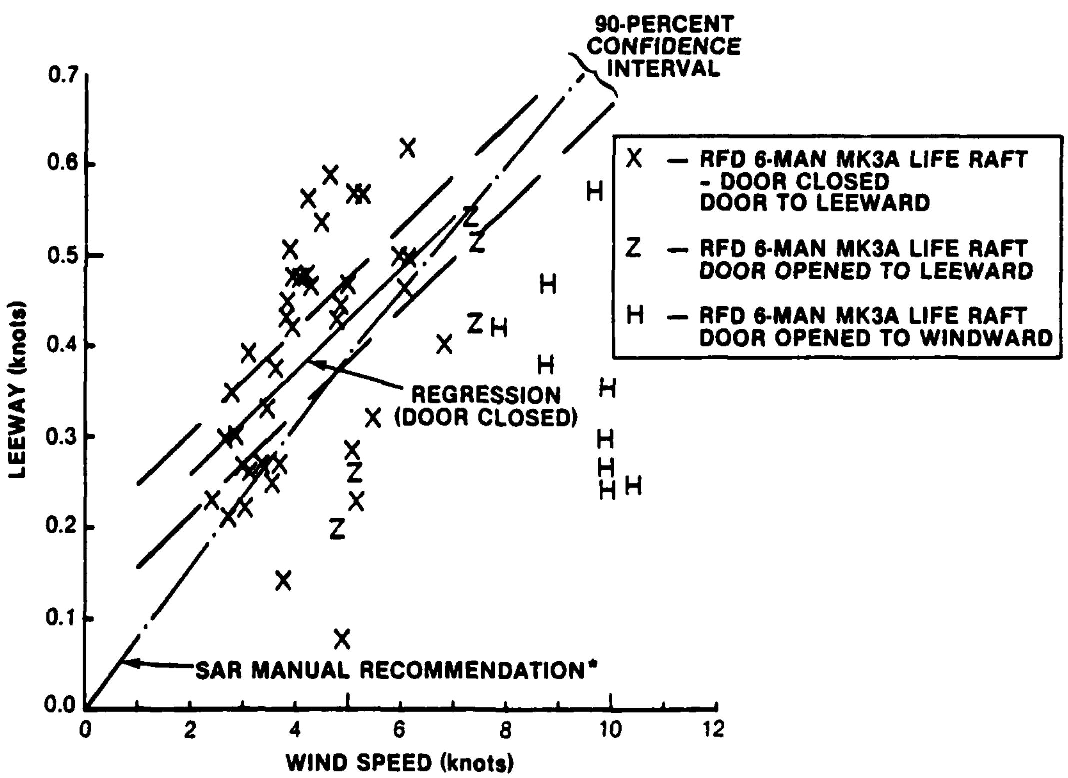


Figure 18. Leeway Speed versus Wind Speed for RFD 6-Man MK3A Life Raft

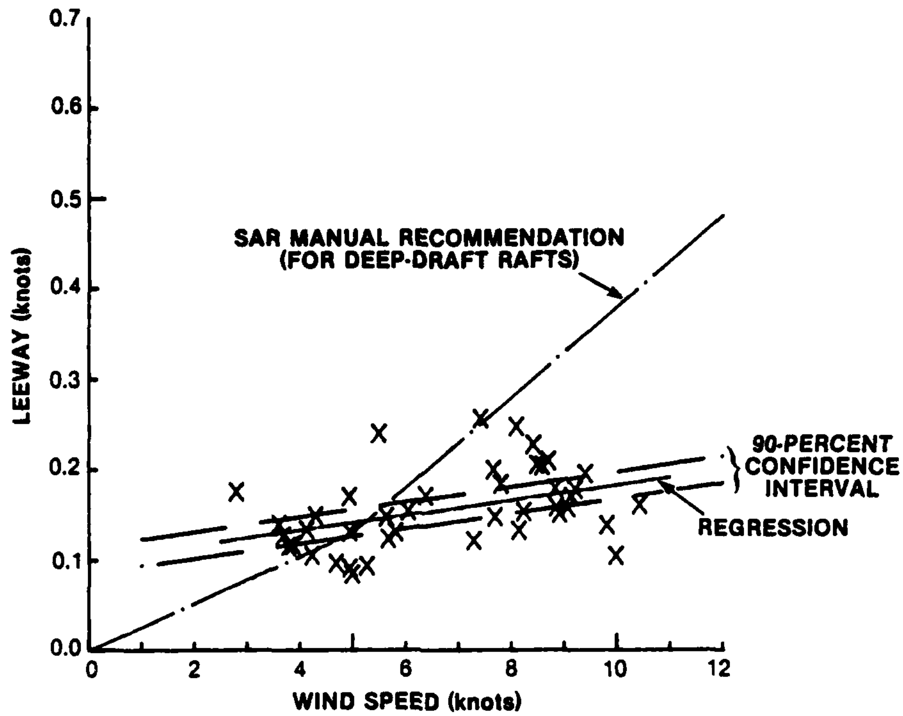


Figure 19. Leeway Speed versus Wind Speed for Switlik 4-Man Life Raft

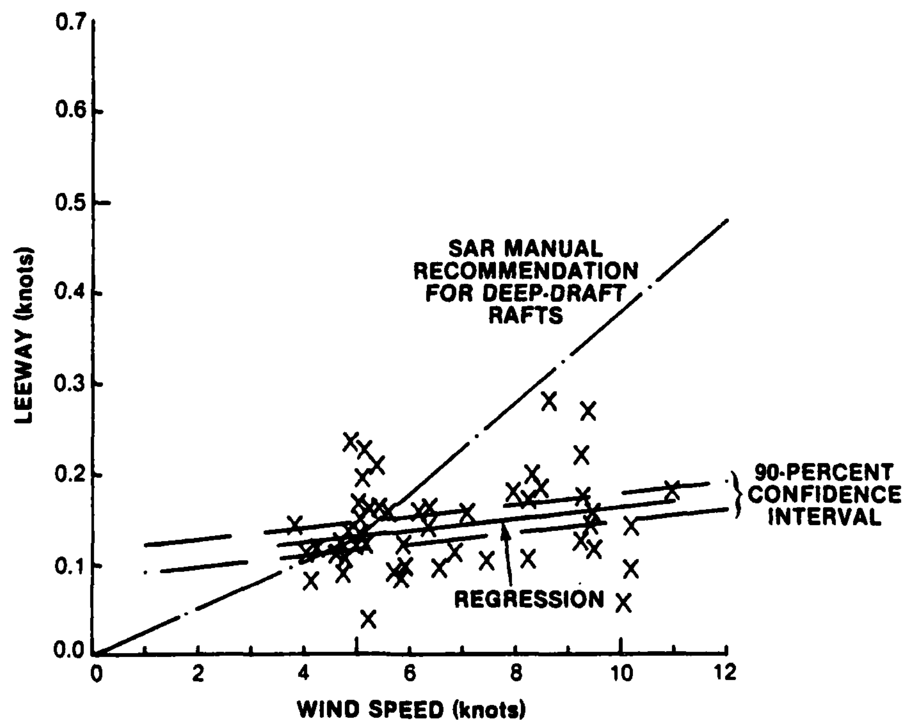


Figure 20. Leeway Speed versus Wind Speed for Givens 6-Man Life Raft

4.4.2 Leeway Rate versus Wind Speed

Leeway rate is defined as the ratio of leeway speed to wind speed, the relationship of leeway rate to wind speed was studied using the same methods used for studying the relationship of leeway speed to wind speed. The regression equations of leeway rate to wind speed are presented in Table 10. The regression equation for the RFD 6-man raft with the door closed is not significant at the 0.05 level (P>0.05). The other two regressions are highly significant. The negative correlation coefficients indicate that leeway rate is inversely related to wind speed. This is graphically demonstrated in Figures 21, 22, and 23. The 90-percent confidence limits for each regression equation were calculated as described in Section 4.4.1.

The scatter in leeway rate data should be greater than the scatter of leeway speed because errors in measuring wind speed are included twice: once in the calculation of leeway rate, and again in the comparison to wind speed. This explains the increased scatter for the RFD life raft (Figure 21) and the resulting low correlation coefficient. For the Switlik and Givens life rafts (Figures 22 and 23), the leeway rate regressions are

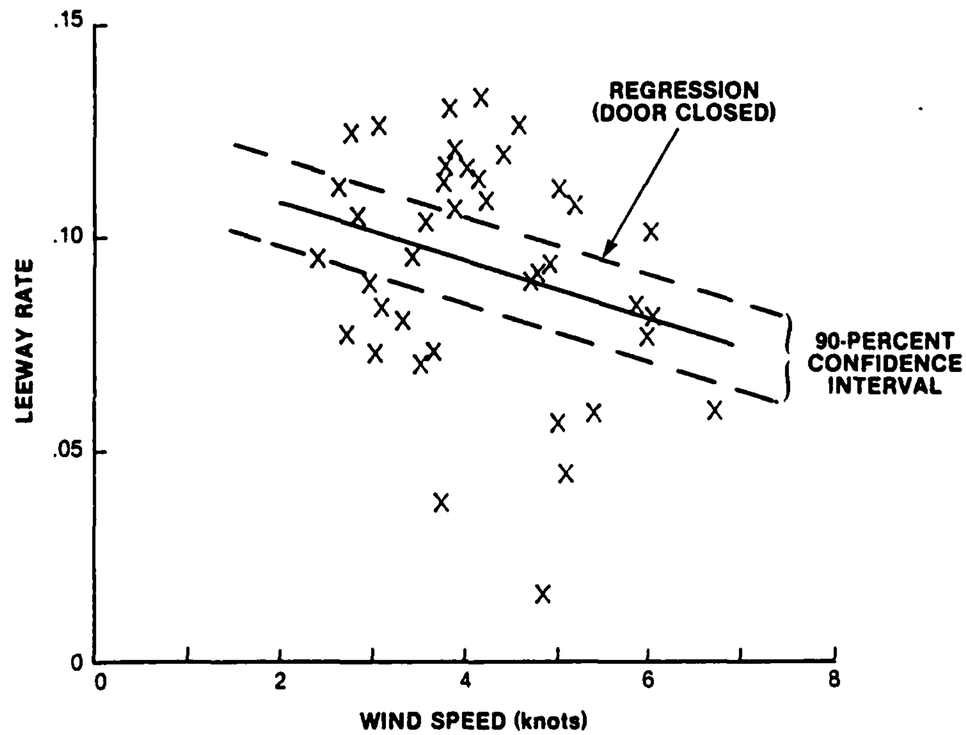


Figure 21. Leeway Rate versus Wind Speed for RFD 6-Man MK3A Life Raft

TABLE 10

RESULTS OF LINEAR LEAST SQUARES REGRESSION AND ANALYSIS OF VARIANCE OF LEEWAY RATE (L_r) TO WIND SPEED (W)

LIFE RAFT	NUMBER OF DATA POINTS	LEEWAY RATE $L_r = a + bW$	90-PERCENT CONFIDENCE LIMITS		CORRELATION COEFFICIENT (r)	STANDARD ERROR OF ESTIMATE (Sy.x)	DOF*		F-STATISTIC	PROBABILITY† (P)
			a	b			REG	RES		
RFD 6-Man (Door closed)	40	0.122 - 0.0068W (0.122 - 0.0132W)	0.094 0.150	-0.0134 - 0.0005 (-0.026 - 0.001)	-0.28	0.026	1	38	3.15	$0.05 < P < 0.1$
Switlik 4-Man	42	0.043 - 0.0026W (0.043 - 0.0051W)	0.037 0.050	-0.0036 -0.0021 (-0.007 -0.004)	-0.63	0.007	1	40	26.70	$P < 0.001$
Givens 6-Man	48	0.037 - 0.0021W (0.037 - 0.0041W)	0.032 0.042	-0.0031 -0.0015 (-0.006 -0.003)	-0.58	0.006	1	46	23.32	$P < 0.001$

NOTE: Values and equations in parentheses are for meters/second (m/s) if different. All others are in knots.

* DOF = degrees of freedom; REG = regression; RES = residual

† Probability of making an error by accepting the regression when leeway rate and wind speed are independent.

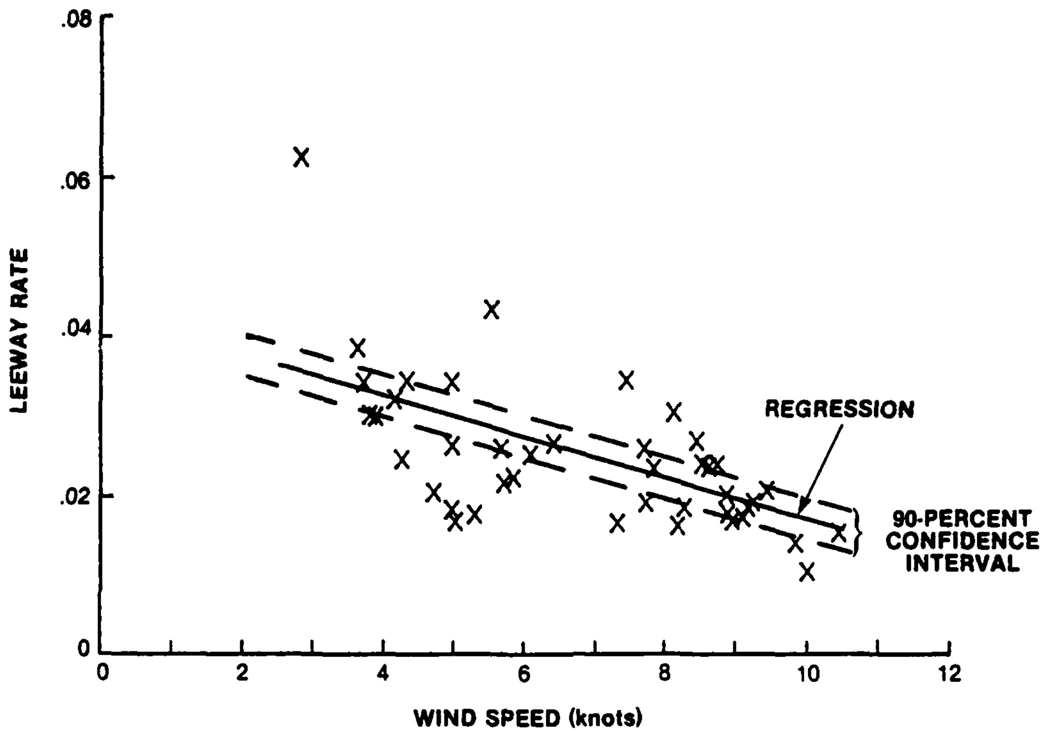


Figure 22. Leeway Rate versus Wind Speed for Switlik 4-Man Life Raft

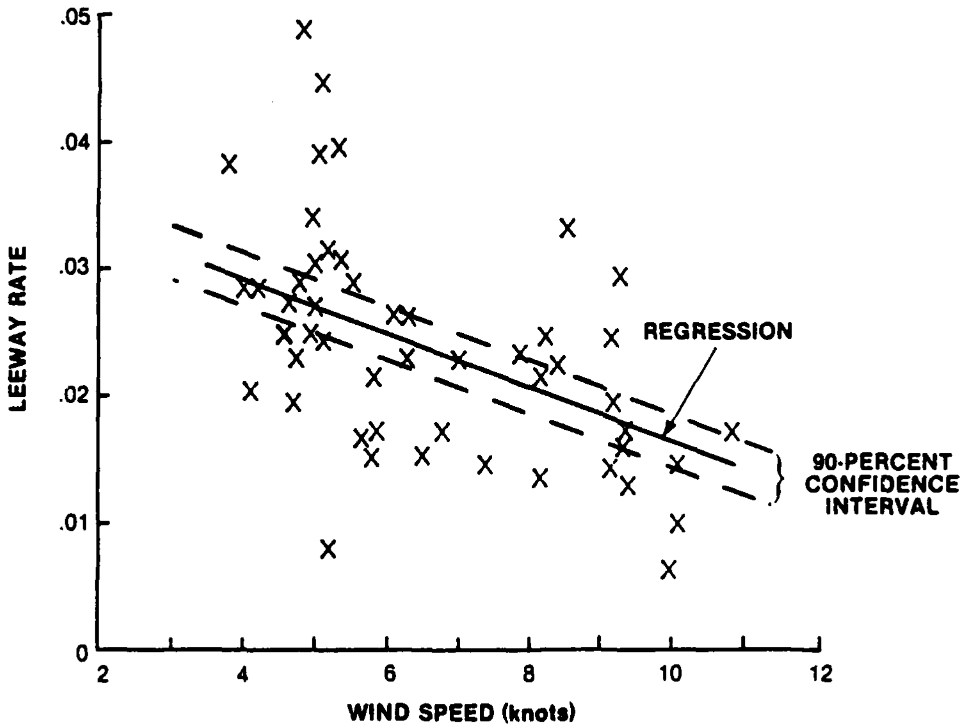


Figure 23. Leeway Rate versus Wind Speed for Givens 6-Man Life Raft

more significant and have stronger correlation coefficients than the leeway speed regressions. This suggests that leeway speed for the deep-draft, ballasted rafts is a non-linear function of wind speed. Over the data's narrow range of wind speeds, a linear relationship of leeway speed to wind speed for the RFD life raft is adequate.

4.5 ERROR ANALYSIS

The two types of error are random error and systematic error. Systematic errors result in values that are always greater or less than the true value. Random errors result in values distributed randomly around the true value. Systematic errors bias the results and are removed by proper calibration and analysis methods. Random errors do not bias the results and are normally overcome by the use of statistical methods.

Systematic and random errors are discussed in Sections 4.5.1 and 4.5.2, respectively. The errors associated with measuring the wind at some location other than the test craft are discussed in Section 4.5.3.

4.5.1 Systematic Errors

The microwave tracking system (MTS) is not expected to be a source of systematic errors as it was calibrated in the usual manner and set up on an established range. The anchored wind sensor was checked against a hand-held anemometer and had been calibrated by the dealer. The alignment of the wind instrument on the raft was checked on each deployment and recovery. As discussed in Sections 4.1.1 and 4.1.2, the wind instrument aboard the life raft probably affected the behavior of the RFD and Switlik rafts. The Givens life raft was not equipped with the wind instrument. The wind instrument (described in Section 2.2.3) has a vertical cross section of 0.69 square feet (neglecting the cups and vane). The rafts have a vertical the cross-sectional area of at least 10.5 square feet. Thus, the wind instrument is less than 0.07 of the cross-sectional area of the rafts. The neglible impact on the leeway speeds is supported by comparing the leeway of the Switlik to that of the Givens.

The method of analysis may be a source of systematic error. All leeway speeds below 0.06 knots (0.03 m/s) were excluded from the data as the corresponding leeway

angles were erratic and unreasonable. The elimination of a significant number of these points would cause the measured leeway speeds to be higher than the true leeway speed. These data points were a small percentage of the total and appear to be outlyers. The authors do not believe that eliminating these data had any significant impact on the results.

4.5.2 Random Errors

Random errors are next to impossible to eliminate, but their effect can be tracked throughout the computations. A simple way to trace the errors is to assume that the addition of two errors (E_1 and E_2) is as follows:

$$\text{Sum of the Errors} = \sqrt{E_1^2 + E_2^2}\ . \qquad \text{(Eq. 5)}$$

The velocity of the raft and the current are calculated using two positions and a time step (ΔT). Thus, the error associated with the velocity calculations (ΔU) using Equation 5 is:

$$\Delta U = \frac{2\,\Delta P}{\Delta T} \qquad \text{(Eq. 6)}$$

where ΔP is position error. Leeway speed is the raft speed minus the current speed. Thus, the leeway speed error (ΔL) given by Equations 5 and 6 is:

$$\Delta L = \frac{2\,\Delta P}{\Delta T}\ . \qquad \text{(Eq. 7)}$$

Leeway rate is the ratio of leeway speed to wind speed. Thus, the error in the leeway rate calculation can be calculated as follows:

$$R \pm \Delta R = \frac{L \pm \Delta L}{W \pm \Delta W} \qquad \text{(Eq. 8)}$$

where:

- R = leeway rate,
- L = leeway speed,
- W = wind speed, and
- Δ = denotes the respective errors.

Solving Equation 8 for ΔR for the larger possible error yields:

$$\Delta R = \frac{\Delta L + R\Delta W}{W - \Delta W} \quad . \qquad \text{(Eq. 9)}$$

Equation 9 indicates that the error in calculating the leeway rate increases with the uncertainty of the wind and higher leeway rates and decreases with increasing wind speeds.

From Chapter 2, the position error for the initial positions is known to be 10.9 yards (10 m). The linear interpolation routine acts as a filter that is assumed to reduce the error by 30 percent. Thus, the new position error is 6.5 yards or 0.0032 nautical miles (6.0 m). The time step (ΔT) is 4 minutes or 0.067 hours. This gives a leeway speed error (ΔL) of 0.1 knots.

The wind speed error (ΔW) is 2 knots (1.0 m/s). For a wind speed of 7 knots (3.6 m/s) and a leeway rate of 0.07, leeway rate error (ΔR) is 0.06. The actual value of the wind speed error for the anchored wind instrument is probably less since the effect of averaging the winds over 4 minutes has been neglected.

The same analysis can be done for directional accuracy, but is more complex and would be highly dependent on the velocities being measured. The higher the velocities or the greater the time step, the smaller would be the directional inaccuracies. The largest source of directional inaccuracies, wind measurement, is discussed in Section 4.5.3.

4.5.3 Wind Measurement Error

The one variable overlooked in the preceding sections was the horizontal variability of the wind field. In the data analysis, when leeway direction was compared to the winds measured on the anchored platform and the monitor boat, it became apparent that the raft was sometimes responding to winds from different directions than those at the anchored platform. The cases where this could be confirmed were eliminated from the data base. No attempt was made to use the monitor boat's wind measurements because there was no assurance that those wind speeds corresponded to the wind speed at the raft.

Thus, some of the scatter in the leeway data is due to the horizontal variability of the wind field. This can only be corrected by monitoring the wind at the test craft or using a time step on the order of one hour.

CHAPTER 5
CONCLUSIONS AND RECOMMENDATIONS

5.1 GENERAL DISCUSSION OF LEEWAY

A linear relationship of leeway speed to wind speed is used in the present leeway models because the underlying research used standard statistical models. The common practice is to assume a linear relationship between parameters unless there is a strong reason to expect otherwise over the range of data. However, extrapolation to wind speeds different from the test conditions will not be valid if the relationship of leeway to wind speed is different than assumed. A non-linear relationship of leeway speed to wind speed has been demonstrated in Pingree (1944), Morgan et al. (1977) (see Figures 1, 2, and 3), and Section 4.4.2. A non-linear relationship is explained by borrowing the concept of a "hull limited" ship from naval architecture. The concept is that each additional unit of propulsion power (wind for leeway) buys a smaller increment of speed due to the increasing drag of the water. Extrapolation to environmental conditions and craft not contained in the data would be permitted using a model based on theoretical constraints.

Leeway is determined in an experiment by subtracting the current from the craft's velocity and correlating the remainder with the wind. In predicting the location of a drifting craft, the search planner calculates the leeway based on a given wind speed and adds the leeway drift to the drift due to the current. The drifting craft is affected by the wind and current from the surface to the top and bottom of the craft, respectively. The wind and the current vary with height and depth, respectively. They may be measured at some distance from the sea or surface or be the average velocity of the air or water between the surface and some reference height or depth. The leeway information in the SAR Manual is based on wind and current using several reference points. The reference points for current varied from the thin layer as marked by a dye patch to a thick layer as marked by a drogued buoy. The reference points of the wind and current used to make predictions are probably different. Failure to account for the vertical profile of the wind and current may decrease the accuracy of predicting the locations of the drifting craft. Whether the accuracy of the present environmental and leeway information makes the issue mute remains to be determined. The issue will definitely become critical with improved information.

Leeway is the wind-induced movement of a craft relative to the water. The craft experiences only the wind relative to the current. A 10-knot wind going in the same direction as a 2-knot current would move a drifting craft at the same speed relative to the water as a 6-knot wind opposing the current. The error from using the true wind instead of the apparent wind (relative to the current) may be acceptable in those cases involving high winds and weak currents. However, the apparent wind should be used in cases involving either low winds or strong currents.

The last element of leeway is leeway angle. The present procedure is to assign an equal probability to all leeway angles between a maximum angle to the right and left of the wind. The procedure also assumes that a craft never changes the side of the wind to which it drifts. Previous studies measured the wind and current at one to two places in the test area but not actually at the test crafts. Thus, some of the variability in the leeway angle is due to the spatial variability of the wind and current. Better information on leeway angles will decrease the size of search areas.

5.2 SUMMARY

The purpose of this experiment was to test a new method of determining leeway. The method differed from previous methods in that:

1. The current was estimated from an array of drifters instead of a single drifter.

2. A land-based microwave tracking system was used to track the rafts and drifters. This provided very accurate positions every 2 minutes on each object.

3. The orientations of the rafts to the wind were monitored to explore reasons for and accuracy of leeway angles. This was done by partially instrumenting the rafts for wind measurements.

4. All analysis was done using the apparent wind relative to the current at the raft. This is important in low winds and strong current.

All three life rafts used in this experiment were (1) undrogued, (2) canopied, (3) circular with diameters of 6 to 7.5 feet, (4) unloaded except for some equipment, and (5) ballasted in some manner. The method was successful in detecting the difference in the leeway speed of the lightly ballasted raft (RFD) from the more heavily ballasted rafts (Switlik and Givens). Leeway angles were correlated with the configuration of the raft and its orientation to the wind.

5.3 CONCLUSIONS

1. A knowledge of the configuration of the raft is essential to understanding its leeway characteristics. A raft whose underwater portion is not symmetric to a vertical axis through the raft's center possesses an "effective" keel. Such a raft will exhibit different leeway angles depending on the wind speed and the raft's orientation to the wind. The RFD 6-man raft went to the right or left of the wind depending on its orientation to the wind. The Switlik 4-man and the Givens 6-man rafts, whose underwater portions are symmetric with respect to a vertical line through the raft's center, drifted directly or very close to downwind.

2. The rafts always assumed an orientation so that the force of the wind was acting on the material between the tubes of the canopy. The individual canopy support tubes were never directly to windward.

3. For the Switlik and Givens rafts, the leeway rate is inversely proportional to the wind speed over the range of data. This observation casts doubt on the assumption of a linear relationship of leeway speed to wind speed.

4. The wind instrument placed on board the RFD and Switlik life rafts provided enough drag to affect the relative wind angles for the Switlik raft and, maybe, the RFD raft. There is no evidence that the leeway speeds were affected.

5. The leeway speeds for the RFD 6-man raft with the door closed were similar to the SAR Manual recommendation for canopied life rafts with ballast buckets.

6. The leeway speeds for the Switlik 4-man and the Givens 6-man life rafts were much slower than the SAR Manual recommendation for canopied life rafts with deep-draft ballast systems. This difference may be apparent because this study used the average current of the upper 3 feet of the water column instead of a much thicker layer used in previous studies.

5.4 RECOMMENDATIONS

5.4.1 Experimental Design

The wind should be fully monitored on board the test craft to eliminate the effects of the wind's spatial variability and to determine the craft's response time. The response time is the interval of time required for a craft to respond to a wind change. Questions to be considered include: Are gusts important in leeway?, Will a wind shift cause a craft to change the side of the wind to which it drifts? The necessary parameters to be recorded are the compass heading of the craft, and the relative wind direction and speed. The sampling rate should be on the order of 1 minute or less.

Any item placed in the raft to simulate the loading of people should have approximately the same density as a person. Water will certainly enter the a raft in rough weather. A raft is designed to survive when it is flooded and loaded with its complement of personnel. The design is exceeded when ballast denser than people (such as sand bags) is used. Water jugs should prove to be an ideal ballasting item.

The quantity of data obtained from an experiment can be increased by:

1. Conducting the experiment in a location with a more spatially uniform current than occurs in Block Island Sound. A location with strong tidal currents and plenty of topographic relief will have very interesting oceanographic features, but those features will make estimating the current from a drifter array very risky.

2. Finding a more robust interpolation scheme for estimating the current from the array of drifters.

5.4.2 Future Research

A leeway model based on theoretical considerations should be developed to reduce the inherent risk in extrapolation.

To correctly model a search object's long-term drift, the tendency of a craft to change its leeway angle from one side of the wind to the other must be addressed. This can be accomplished by: (1) studying a craft's response to different frequencies of wind shifts and the variability of the wind fields, and (2) conducting long-term drift studies. A long-term drift study should have drift periods exceeding 36 hours and containing at least one wind shift.

Research should include some estimate of the vertical profiles of wind and current used in drift predictions. This estimation method could be used either directly in the Computer Assisted Search Planning system (CASP) or to ensure the compatibility of the various leeway data and should resolve the difference between Scobie and Thompson (1979) and this report concerning the leeway of deep-draft, ballasted life rafts.

Leeway data on deep-draft, ballasted life rafts with drogues should be collected as there is no information available at this time.

5.4.3 Operational Leeway Guidance

There is a significant difference between the leeway information in the SAR Manual and in this report for canopied, deep-draft, ballasted life rafts. The difference cannot be adequately resolved at present. The authors recommend that the uncertainty be taken into account when making drift predictions. The present SAR Manual recommendation should be used as the upper limit. The lower limit could be either zero leeway similar to a person-in-the-water or a speed of 0.1 knots for winds of 5 knots or greater.

Circular life rafts with the underwater portion symmetric about a vertical axis through the raft's center have small, if any, true leeway angles. The present guidance is to use a leeway angle of ± 35 degrees. A value of ± 10 degrees is adequate if the apparent wind relative to the current is considered. Otherwise, a higher value should be used depending on the current and the wind. This procedure assumes that the variability or uncertainty of the wind and current is addressed elsewhere in the prediction.

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